Light at the end of the beam pipe: Studying Matter under Extreme Conditions

Brookhaven National Laboratory
Office of Science | U.S. Department of Energy
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Hard probes, (some) hard facts; perfect fluids, and sticky issues...

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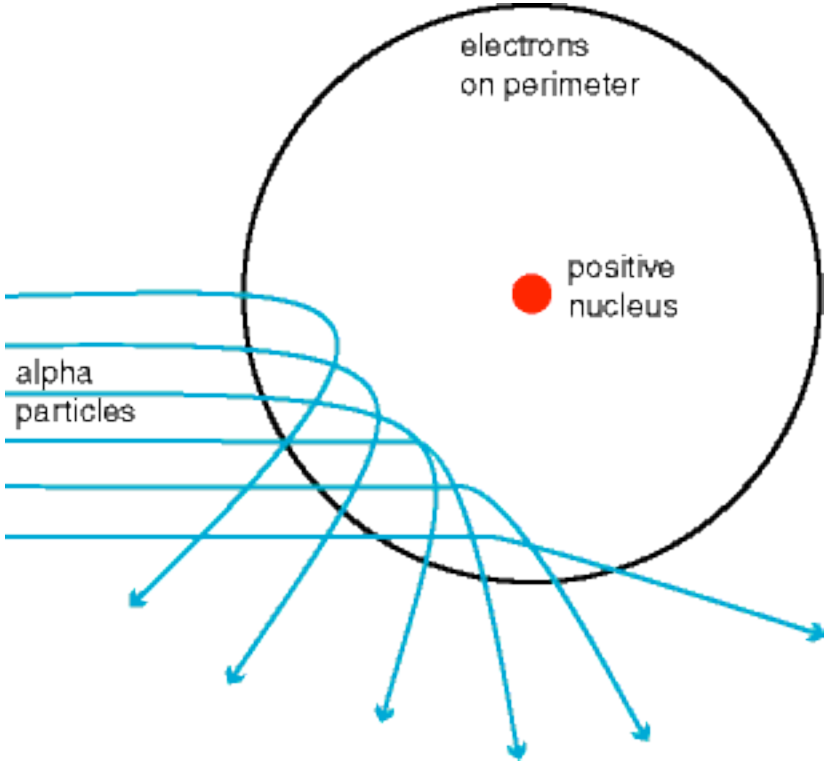
Outline

- Why study heavy ion collisions
  - Furthers our understanding of QCD
  - How to do this?
    - Direct observation of hadronic observables
    - Send penetrating probes & observe response: Tomography
- The RHIC program: Surprises and new physics
  - The quantitative success of relativistic hydrodynamics
  - Photons and dileptons at RHIC
- A new era begins: the LHC
- Conclusion

Going way back: The discovery of the atomic nucleus [1911]



Rutherford and his group bombarded a thin foil of Au with α-particles and noted some *large-angle scatterings.*

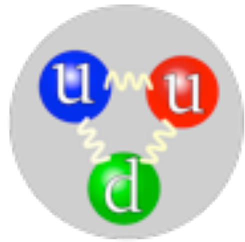
$$\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 E^2}{4E} \right)^2 \frac{1}{\sin^4(\theta/2)}$$

Going deeper: Experimenting on the nucleon (proton) [1953]

Robert Hofstadter

Rudolf Ludwig Mössbauer

The Nobel Prize in Physics 1961 was divided equally between Robert Hofstadter *"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"* and Rudolf Ludwig Mössbauer *"for his researches concerning the resonance absorption of gamma radiation and his discovery in this connection of the effect which bears his name"*.



Nobel Prize 1961: e-p elastic scattering.

The proton has a finite size

Going deeper (cont'd): Experimenting on the nucleon (proton) [1968]

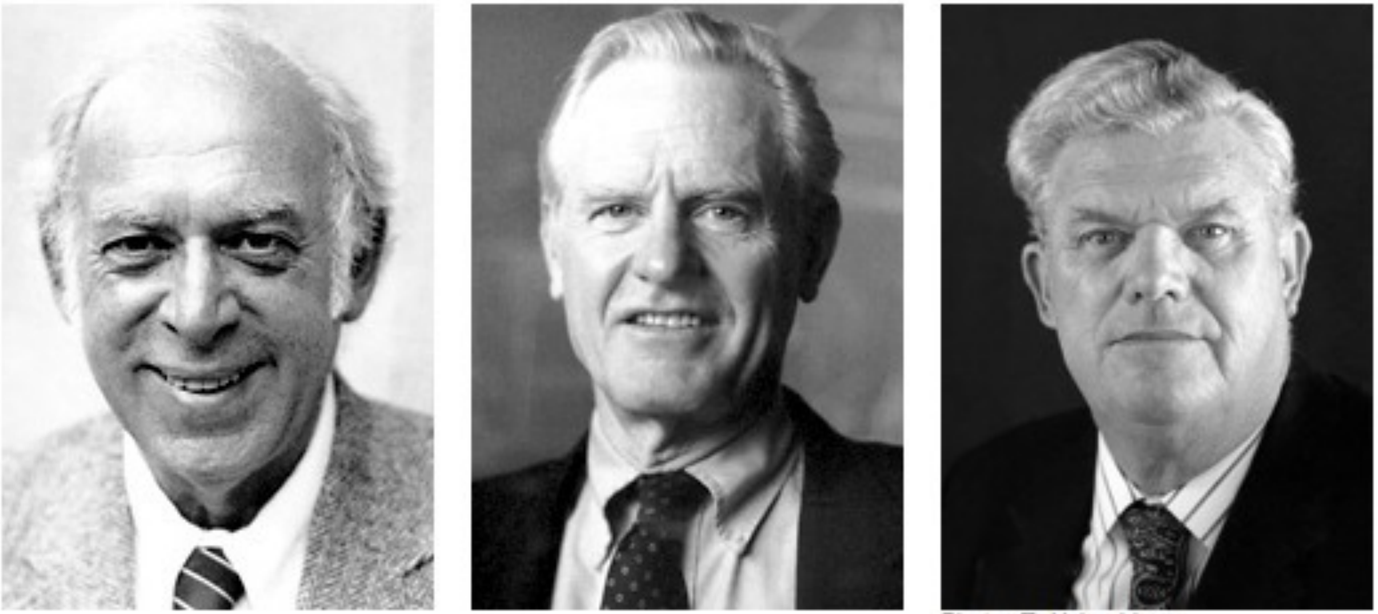
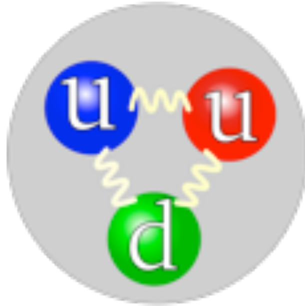


Photo: T. Nakashima

Jerome I. Friedman — Henry W. Kendall — Richard E. Taylor

The Nobel Prize in Physics 1990 was awarded jointly to Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor *"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics".*



Nobel Prize 1990: e-p deep inelastic scattering.

The proton has substructure: Quarks

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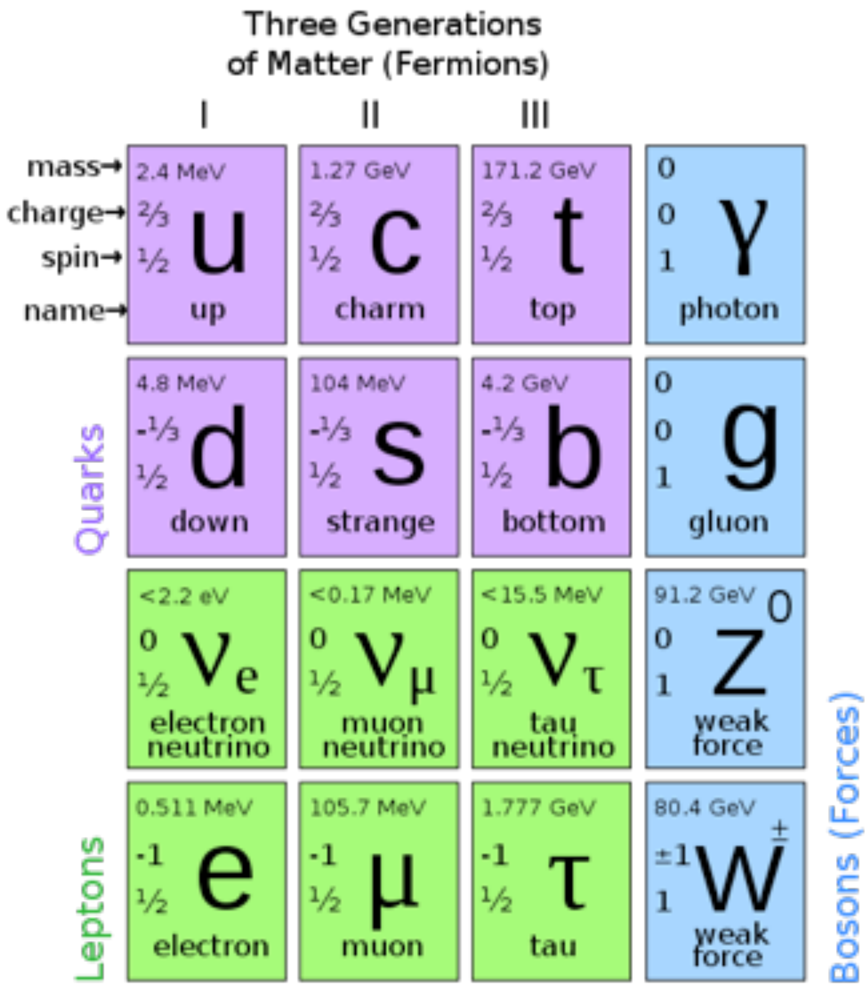
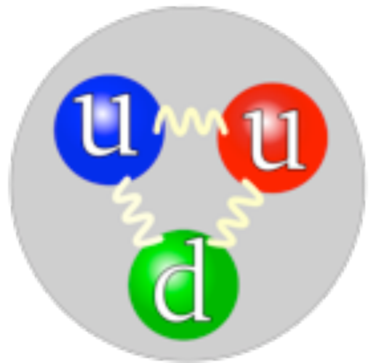
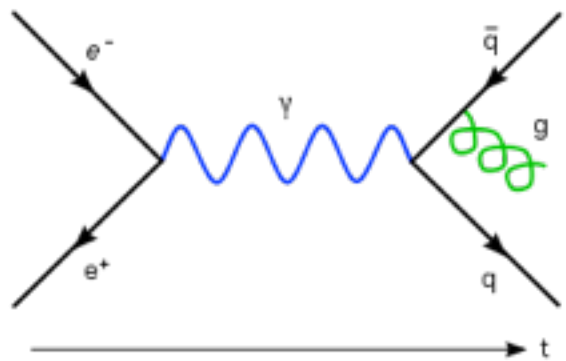
Fast-forward to today: The theory of the strong interaction is QCD. The cast of characters:





Quark structure of the proton



Bosons mediate interaction

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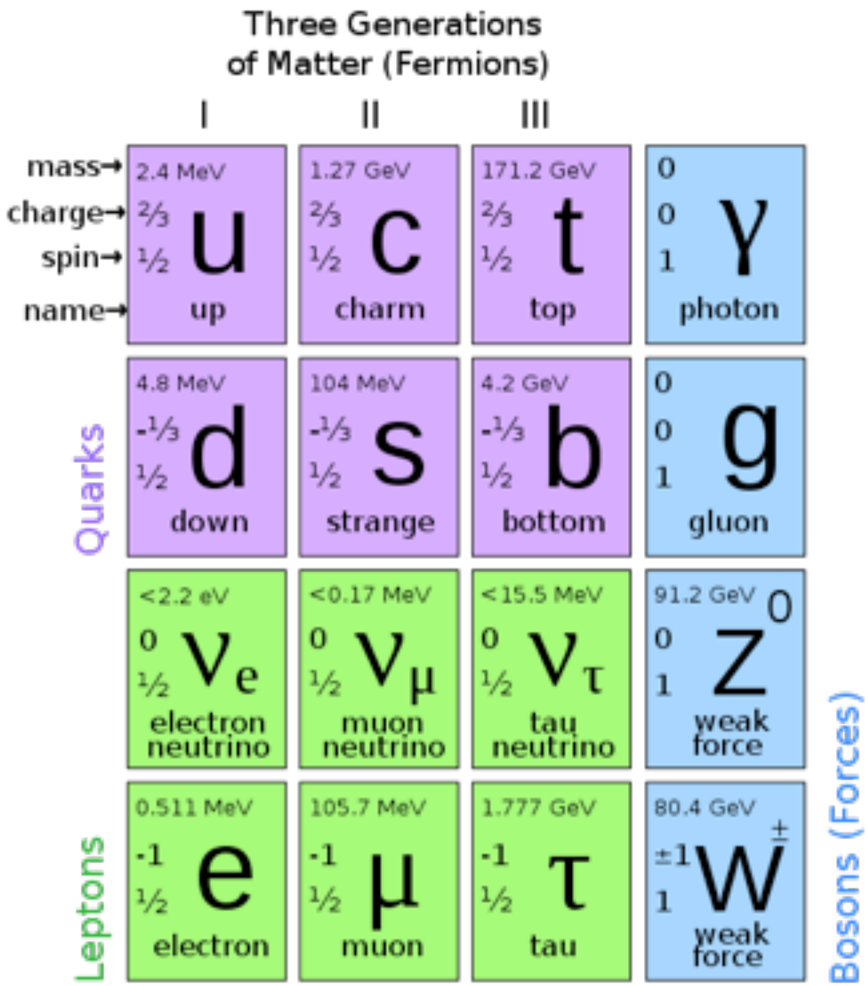
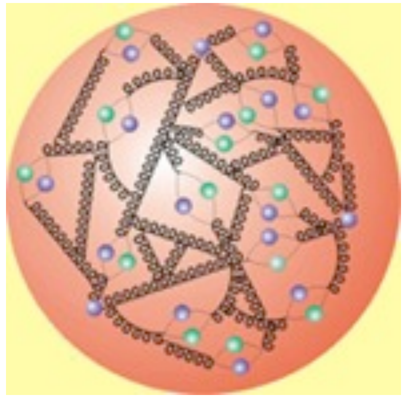
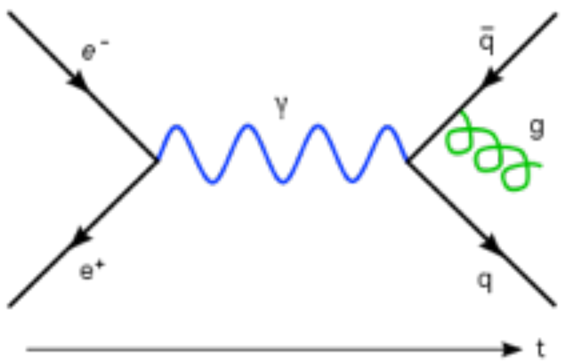




Quark structure of the proton



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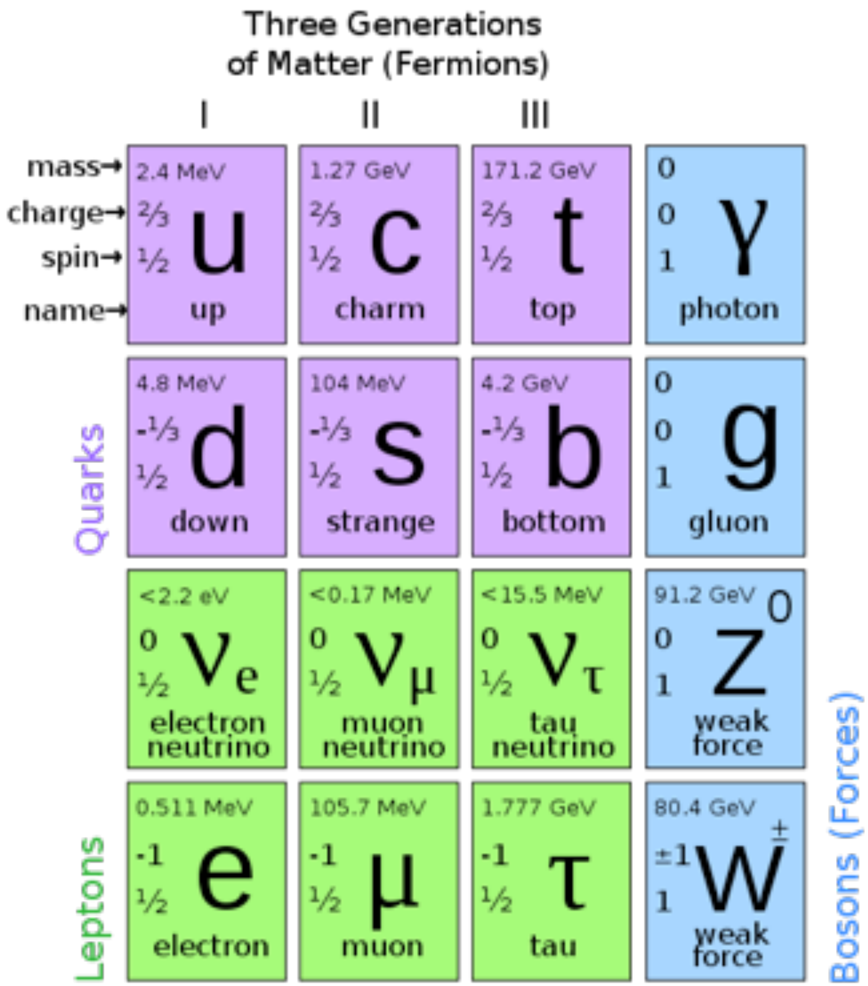
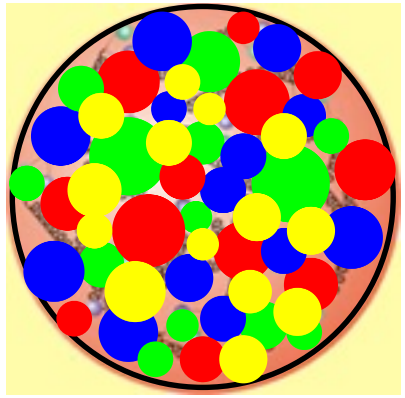
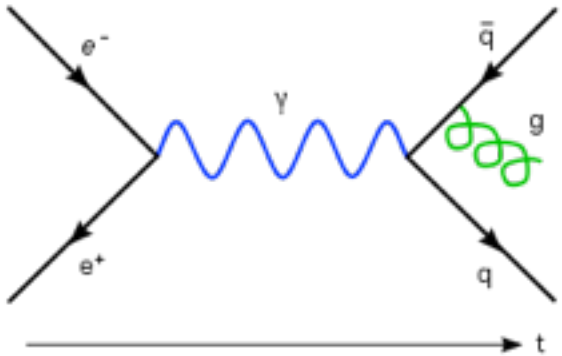




Quark structure of the proton



Bosons mediate interaction

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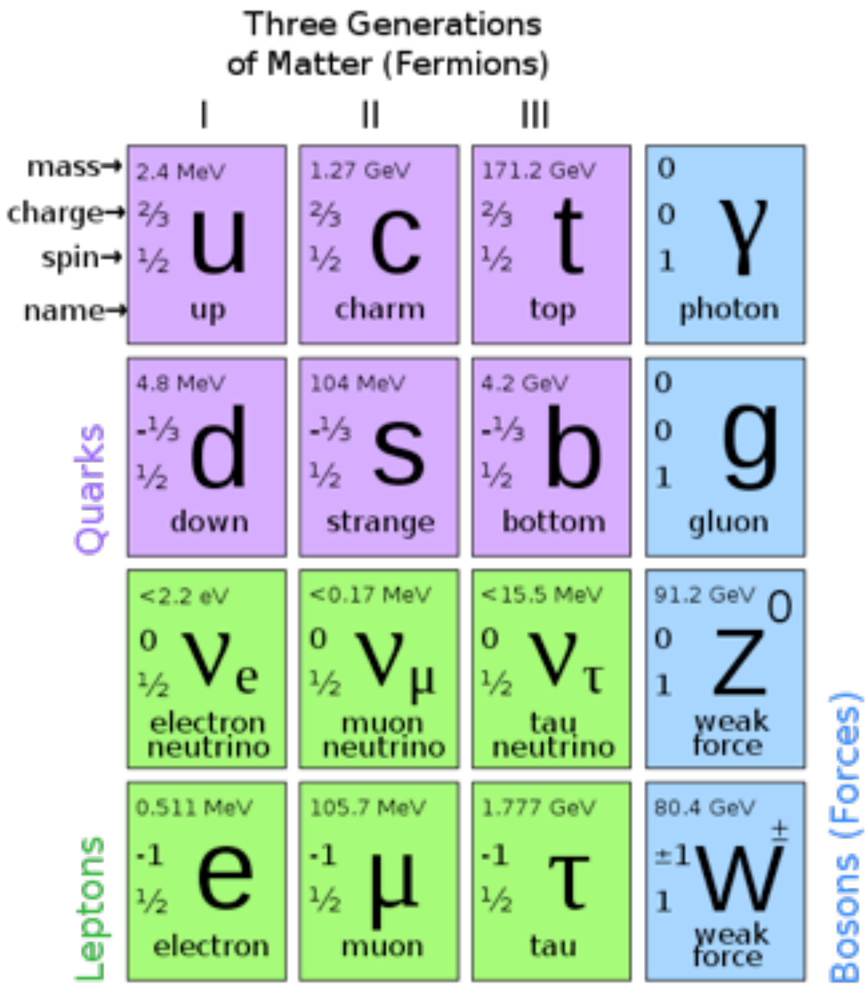

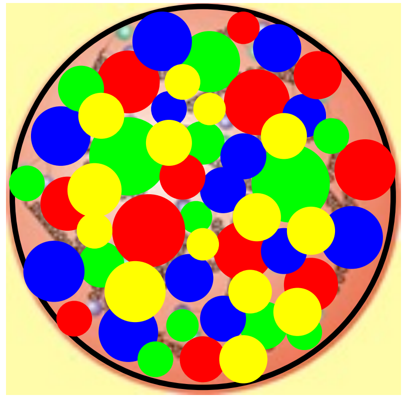

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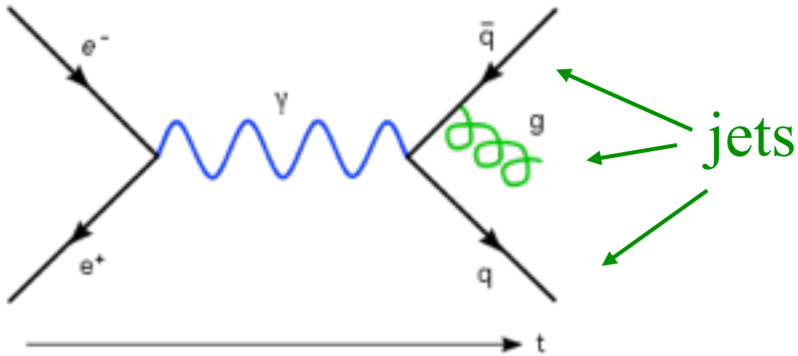


Bosons mediate interaction

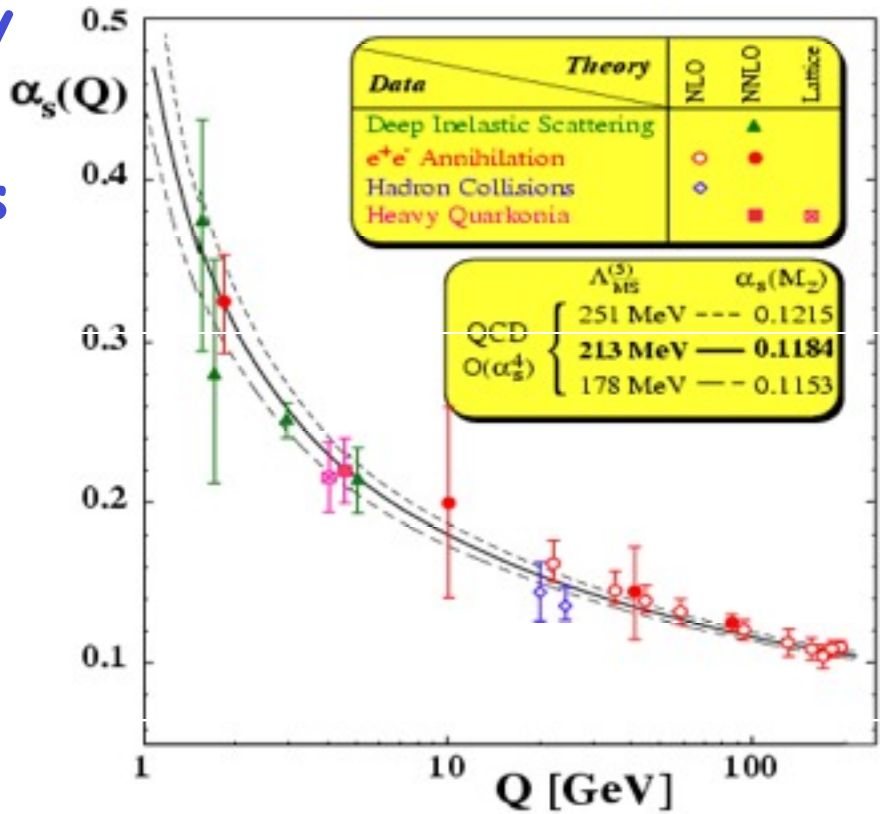
Properties of the source: QCD

- QCD is a gauge field theory that describes the strong interaction of colored quarks and gluons

- QCD "potential"

$$V = -\frac{\alpha_s}{r} + \sigma r$$

  - Asymptotic freedom at short distance
  - Confinement at large distance



S Bethke, Nucl. Phys. Proc. Supp. **121**, 74 (2003)

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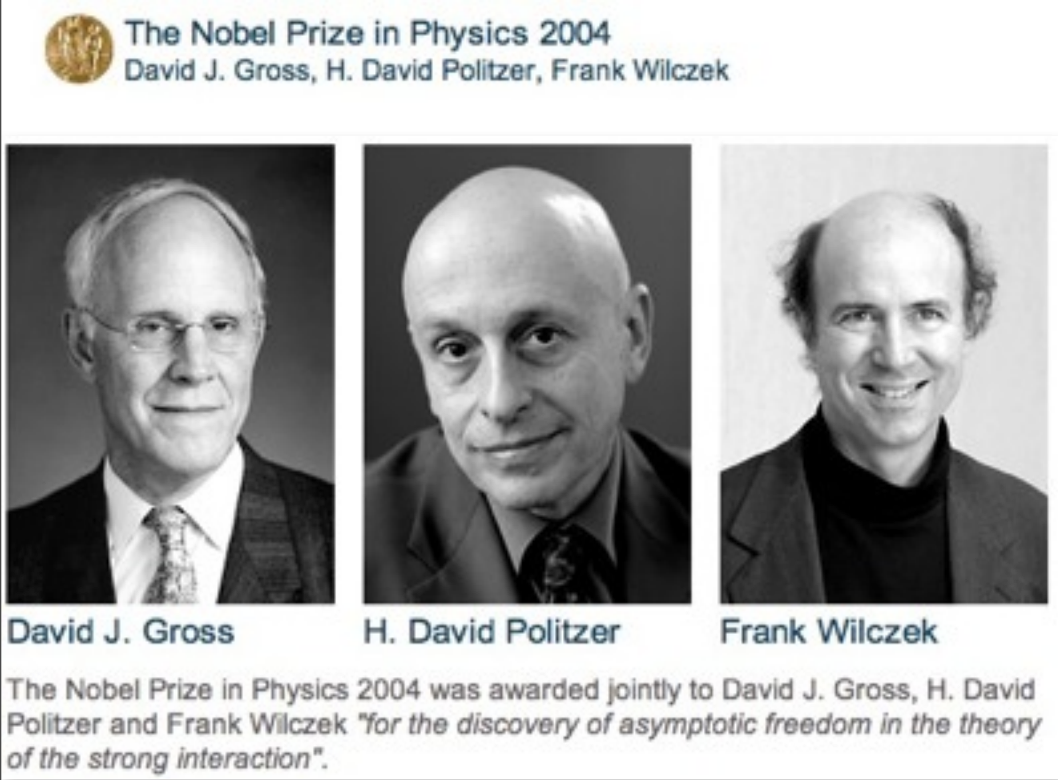
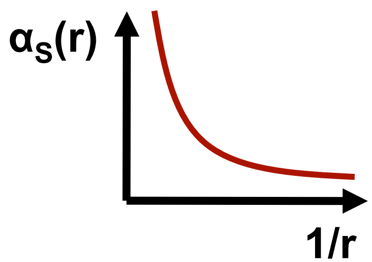


Asymptotic Freedom

“What this year's Laureates discovered was something that, at first sight, seemed completely contradictory. The interpretation of their mathematical result was that the closer the quarks are to each other, the *weaker* is the 'colour charge'. When the quarks are really close to each other, the force is so weak that they behave almost as free particles. This phenomenon is called ‘asymptotic freedom’. The converse is true when the quarks move apart: the force becomes stronger when the distance increases.”



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QCD? Don't we know about QCD??

$$\mathcal{L} = \overline{\psi}(i\not\partial - M - g \not A_a G^a)\psi - \frac{1}{4} F_a^{\mu\nu} F_{\mu\nu}^a$$

$$F_a^{\mu\nu} = \partial^\mu A_a^\nu - \partial^\nu A_a^\mu - g f_{abc} A_b^\mu A_c^\nu$$

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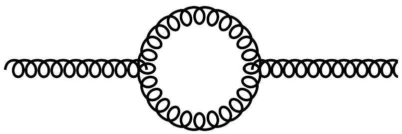

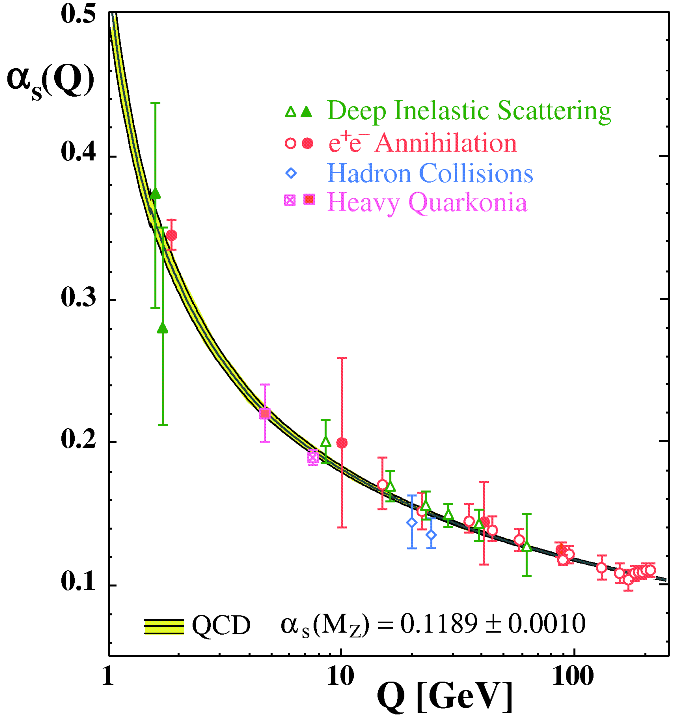

$$\alpha_s(Q) = \frac{g_s^2}{4\pi} = \frac{1}{\ln(Q/\Lambda)}(1+\ldots)$$

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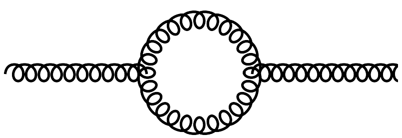

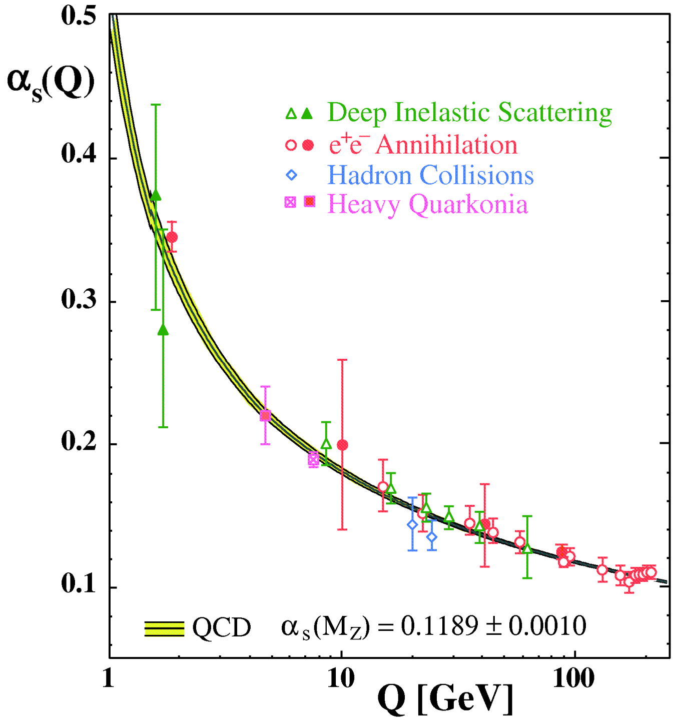

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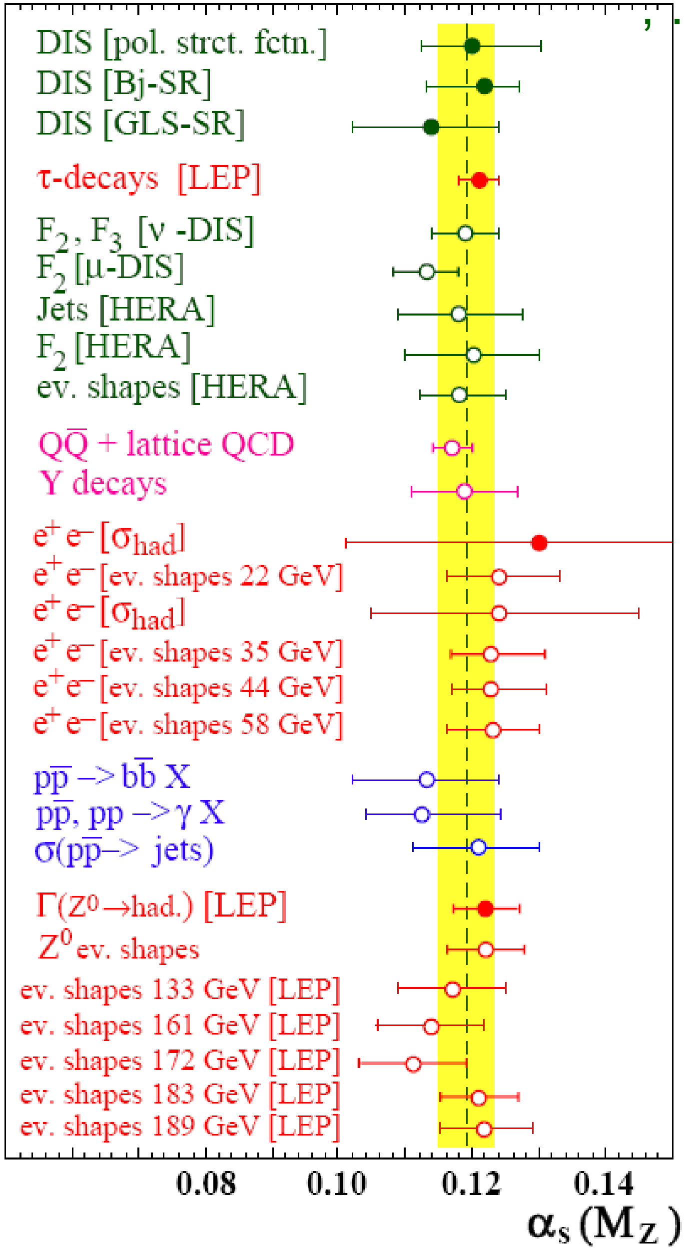

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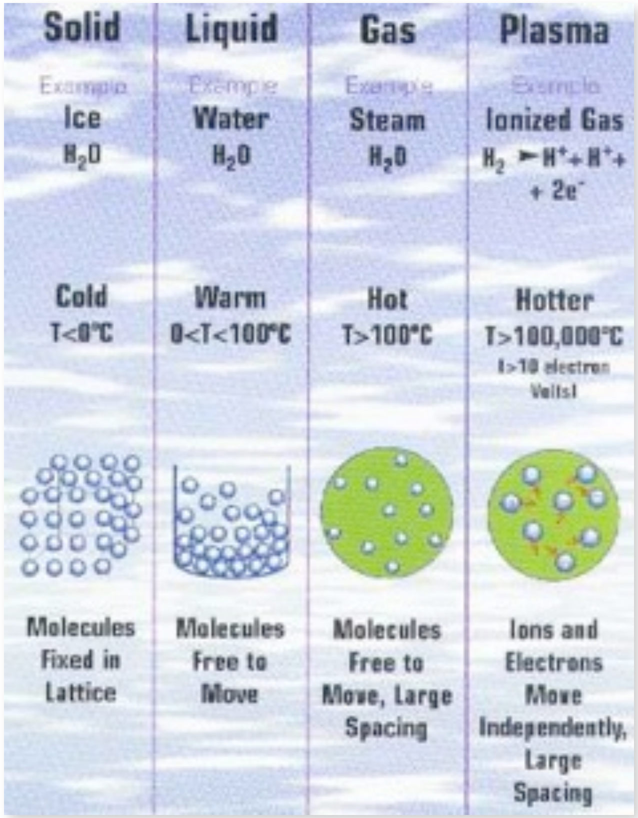
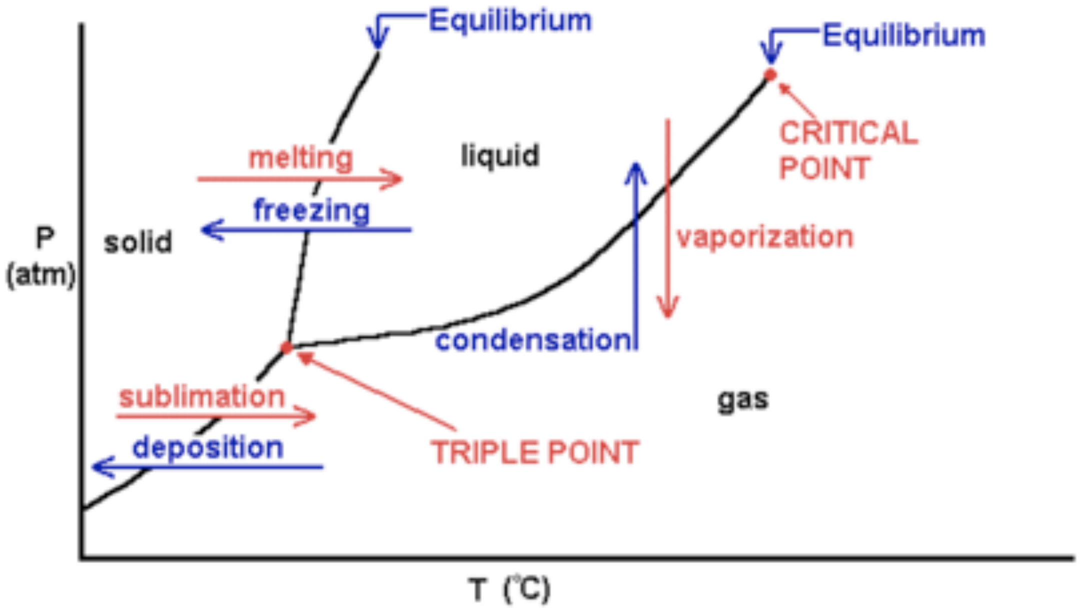
QCD: What we know less…

- Phase transitions in QCD? What is the phase diagram?
- Dynamics of deconfinement, hadronization
- Are there collective features (many-body) effects that are present in QCD at high density/temperatures that are not there at T=0? ("emergent features")
- Does the QCD phase diagram have consequences for cosmology and for dense stellar objects?

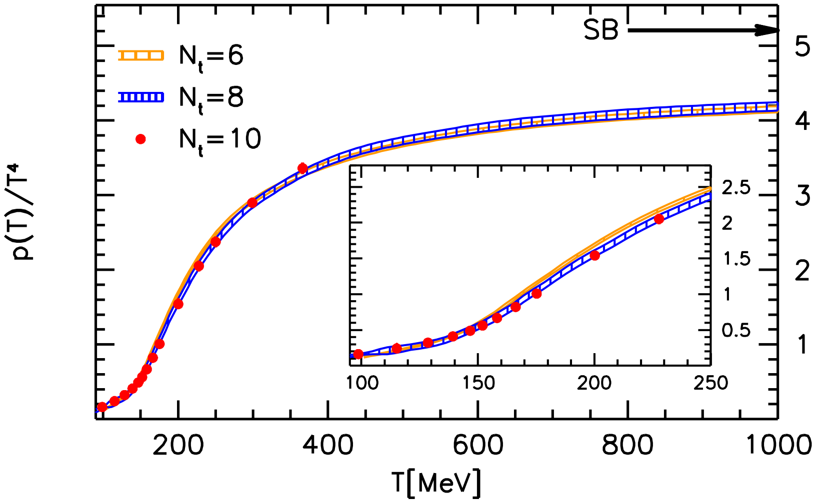
Phase diagram?

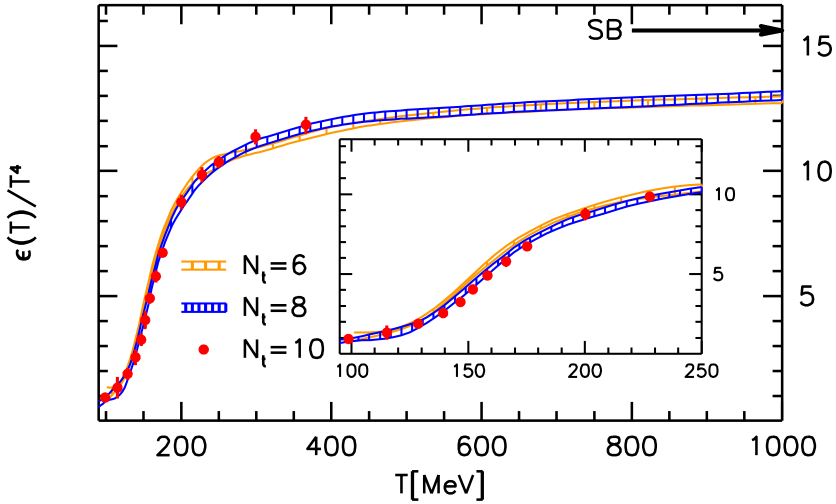


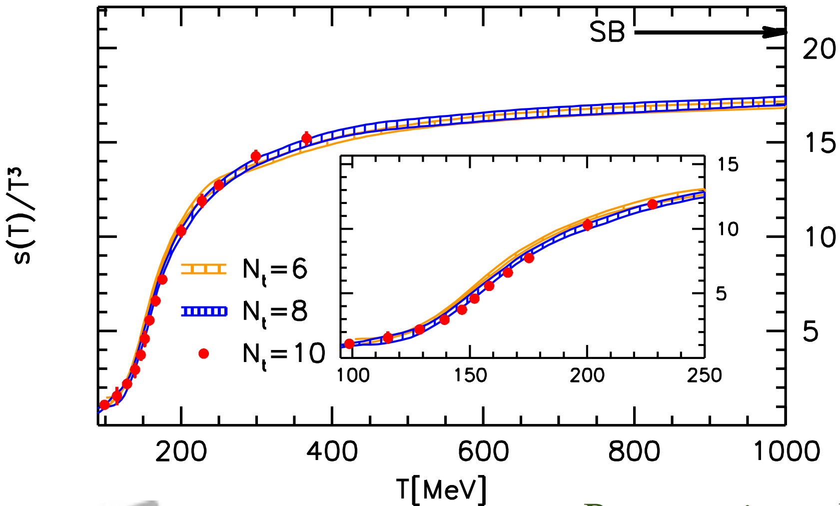


Heating and/or compressing takes us from one phase to another

Some aspects of the phase diagram, we do know from first principles: Lattice QCD (at μ_B=0)







$$\frac{\epsilon}{T^4} = g_{\mathrm{Eff}} \frac{\pi^2}{30}$$

- Slow convergence to SB
- Transition is not sharp

Borsanyi et al.,arXiv:1007.2580

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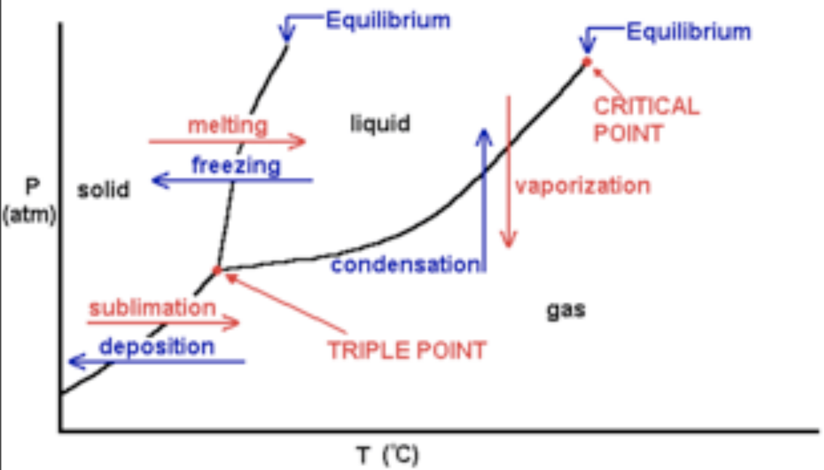
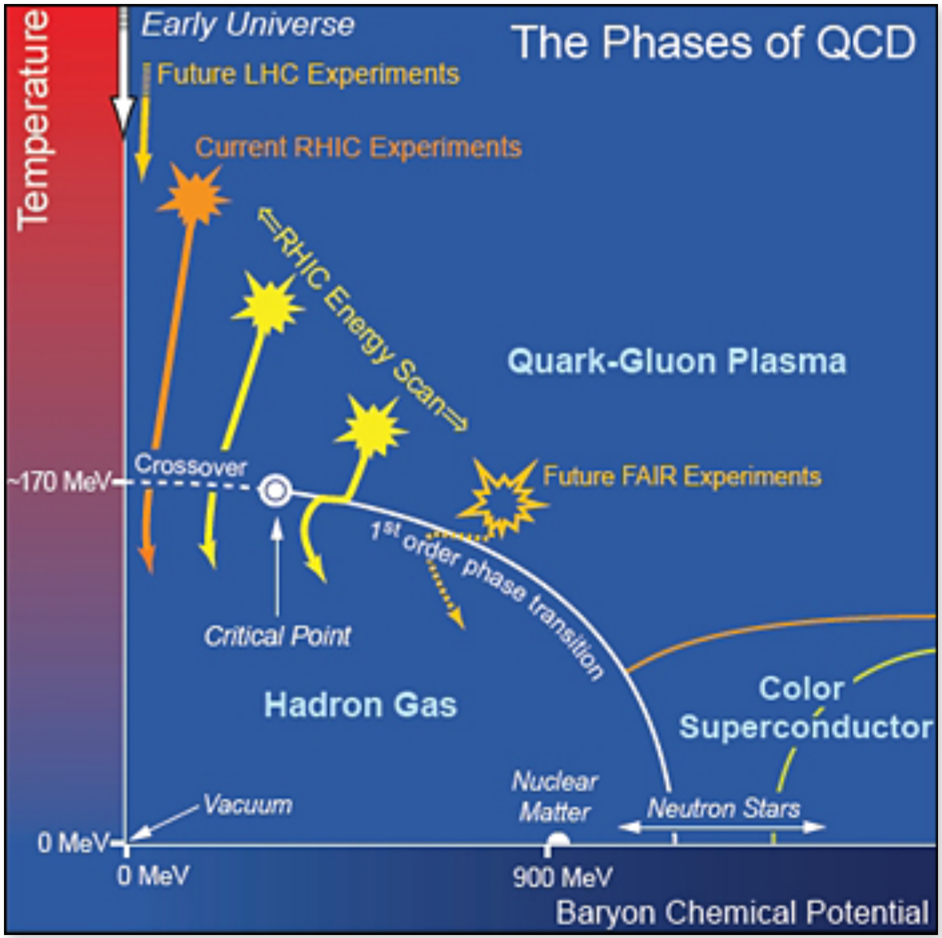
Exploring the QCD phase diagram: Has to be done dynamically





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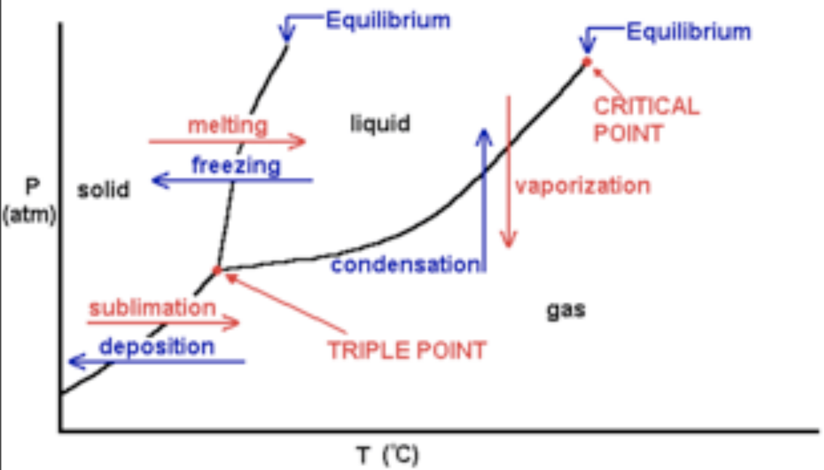

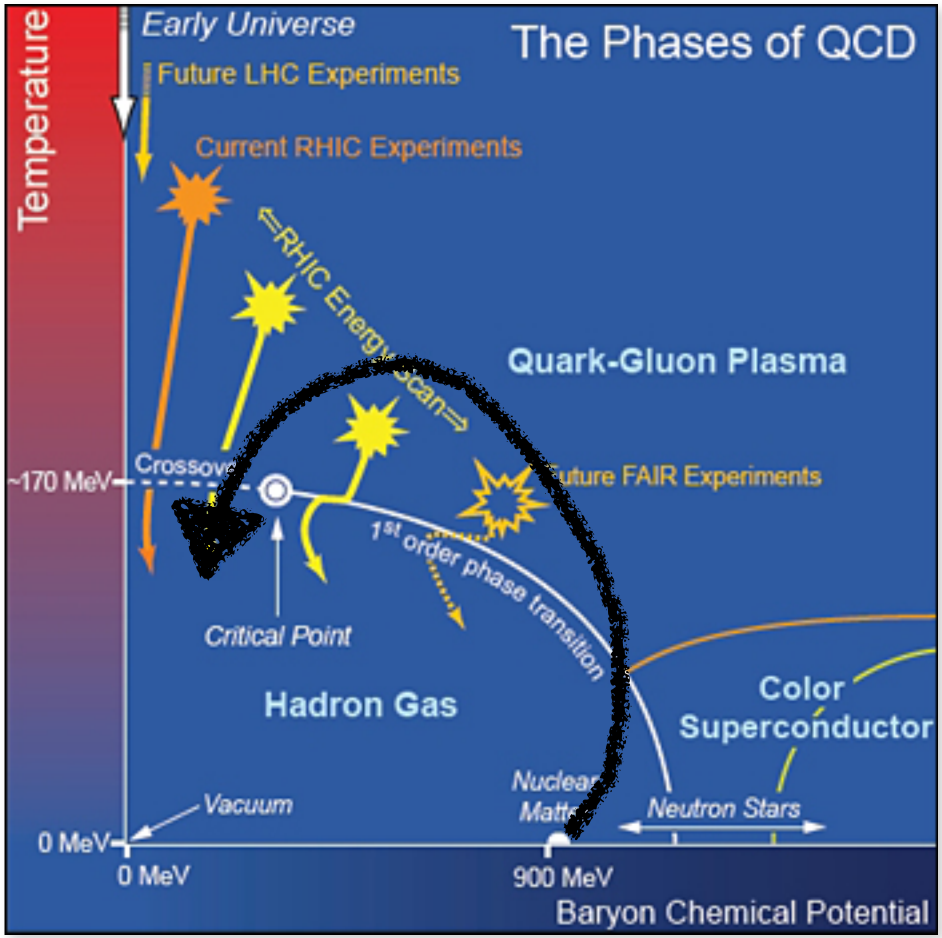

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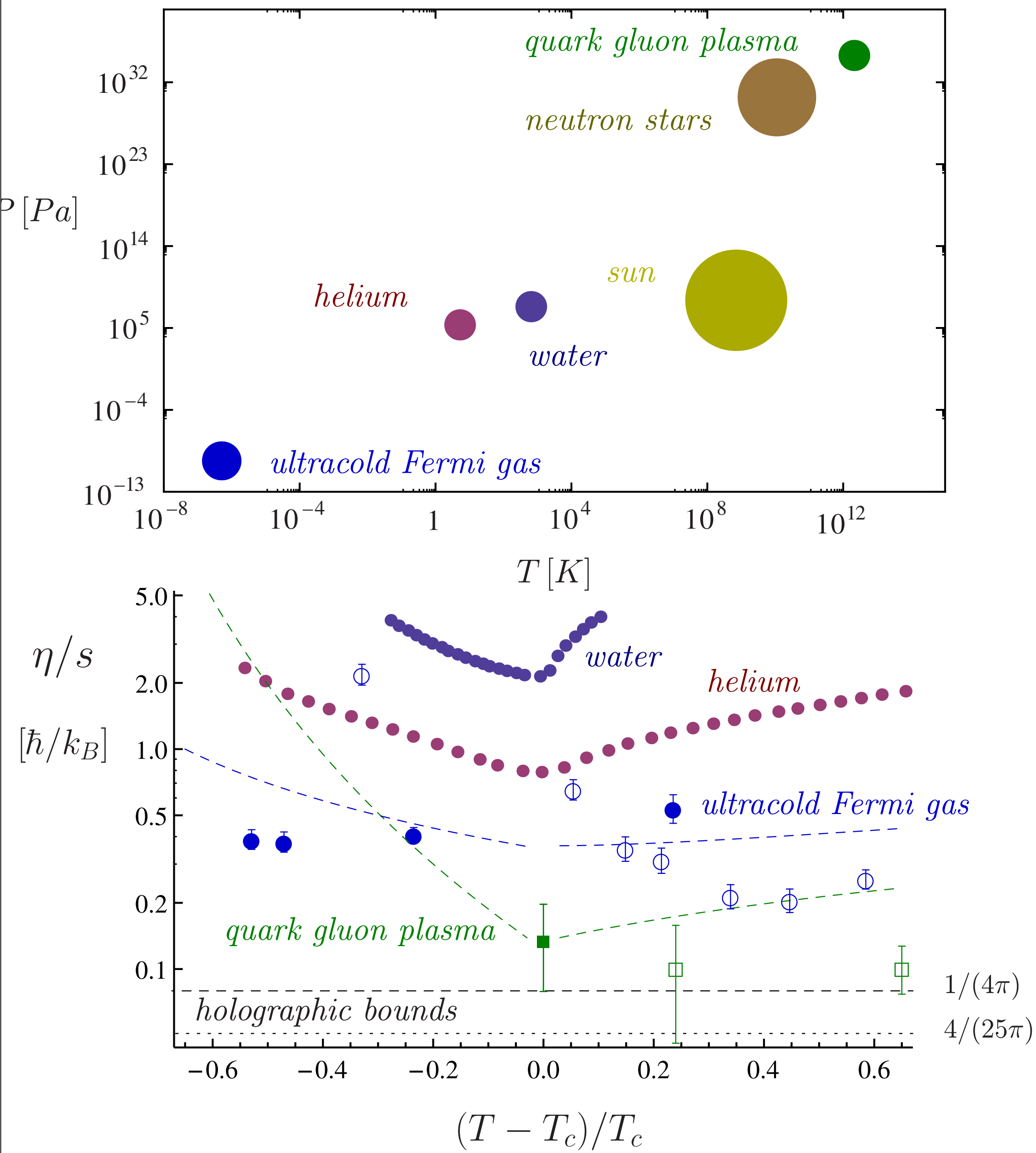
Extreme states: the company we keep



- *The temperature scale spans 19 order of magnitude*
- *The pressure scale spans 44 orders of magnitude*
- *Strongly correlated quantum fluids; their hydrodynamic behavior is similar*

Adams, Carr, Schaefer, Steinberg, Thomas, NJPhys 2012

How to compress and heat nuclear matter: Relativistic nuclear collisions

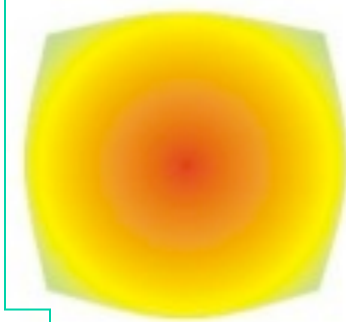
τ

Initial hard collisions

pQCD
Parton picture

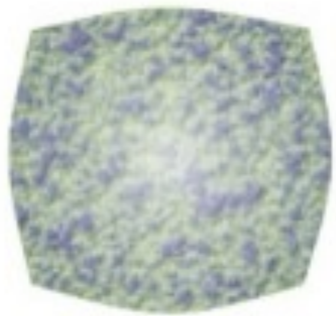
Pre-equilibrium
+
Thermaliza-tion

CGC
Minijets
+
Boltzmann eq.
Out-of-Eq. QFT



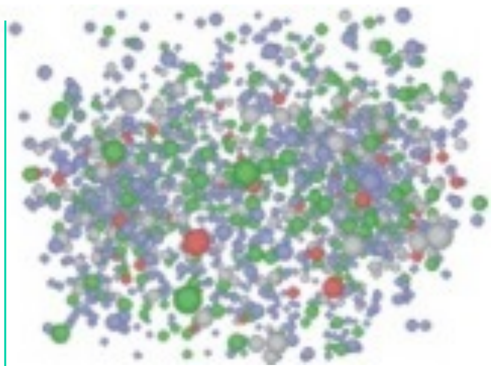
QGP

Relativistic hydrodynamics



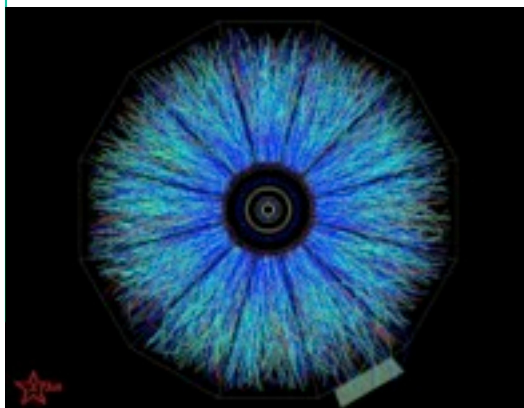
Hadronic phase

Relativistic hydrodynamics



Picture by S. Bass

Free streaming



How to compress and heat nuclear matter: Relativistic nuclear collisions *(Animation: UrQMD)*

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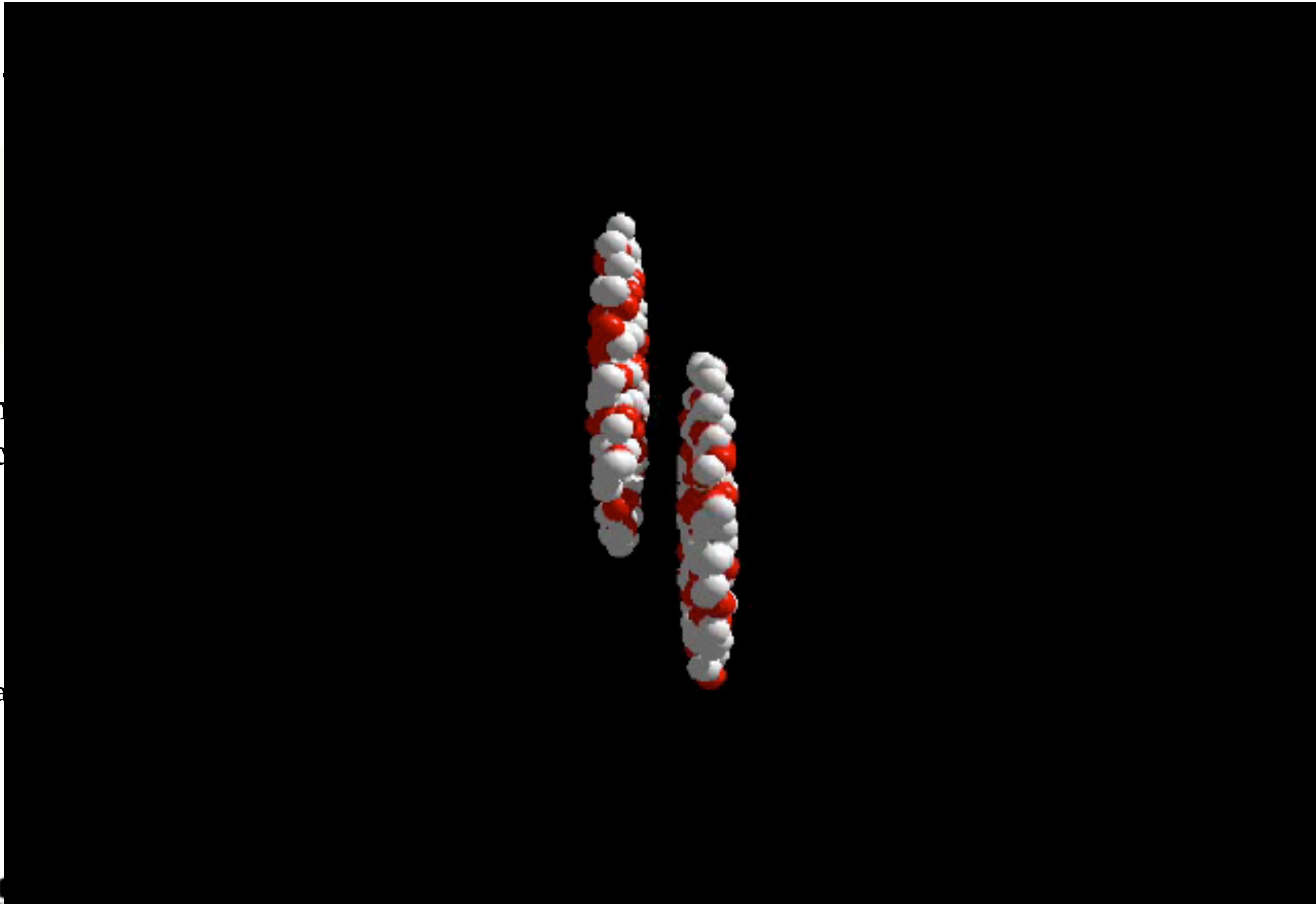
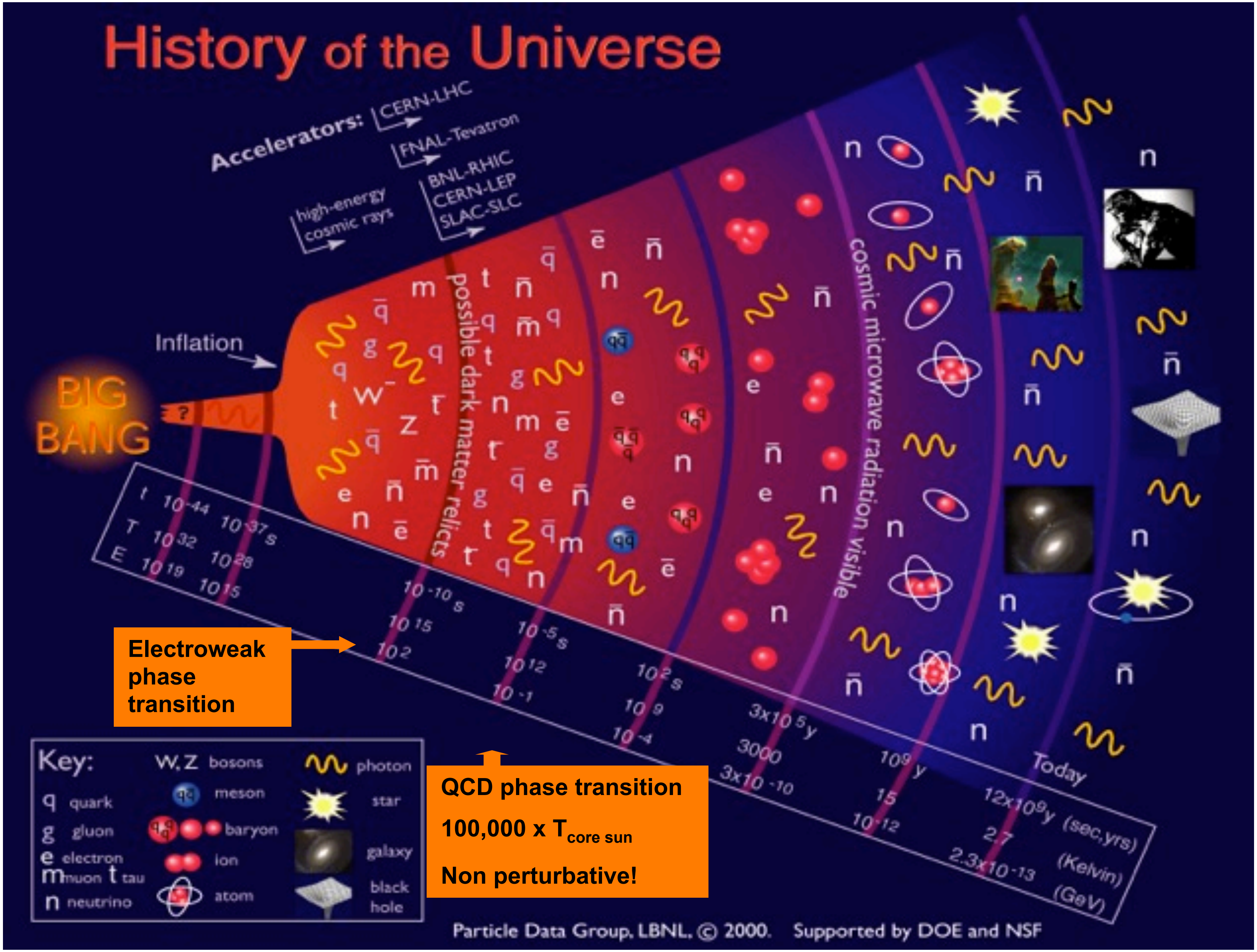


Bass

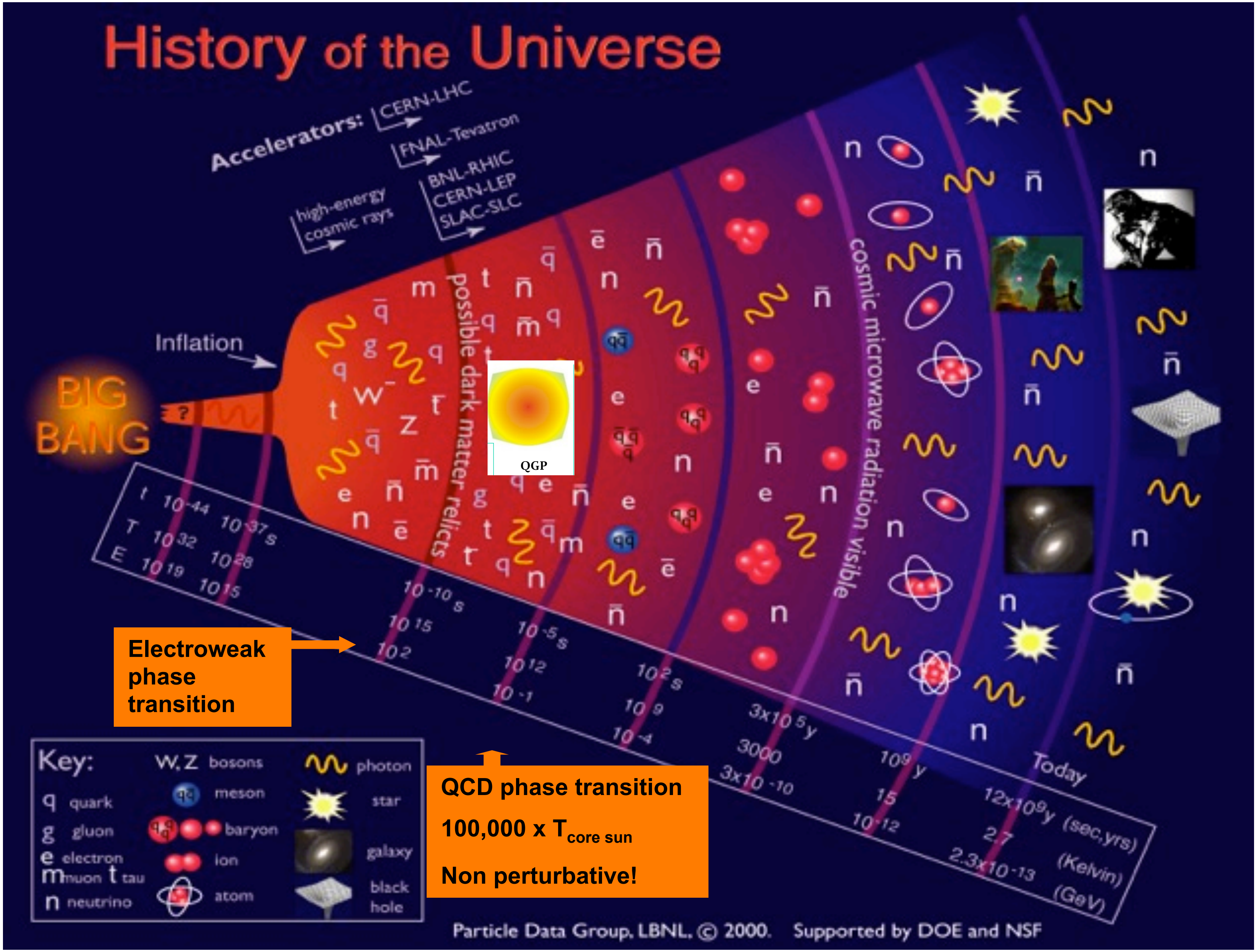


Electroweak phase transition

QCD phase transition

100,000 x $T_{\text{core sun}}$

Non perturbative!



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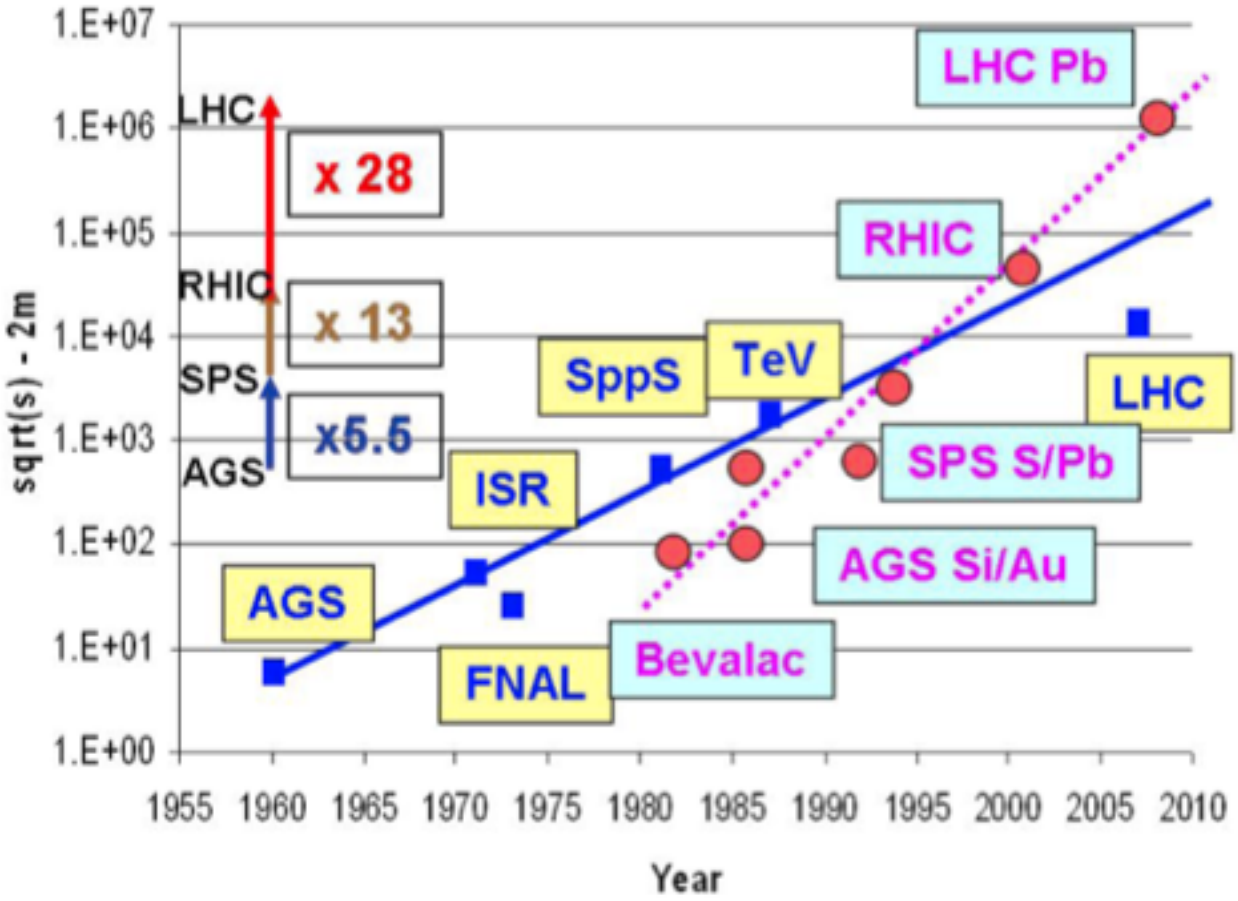
- Bevalac (LBL)
  - fixed target (1975-1986) √s <2.4 GeV
- SIS (GSI)
  - fixed target (1989-) √s <2.7 GeV
- AGS (BNL)
  - fixed target (1986-1998) √s <5 GeV
- SPS (CERN)
  - fixed target (1986-2003) √s <20 GeV
- RHIC (BNL)
  - collider (2000-) √s <200 GeV
- LHC (CERN)
  - collider (2008-) √s <5500 GeV

Livingston plot



J. Schukraft, nucl-ex/0602014

$\sqrt{s}$ <2.7 GeV

- AGS (BNL)
  - fixed target (1986-1998) $\sqrt{s}$ <5 GeV
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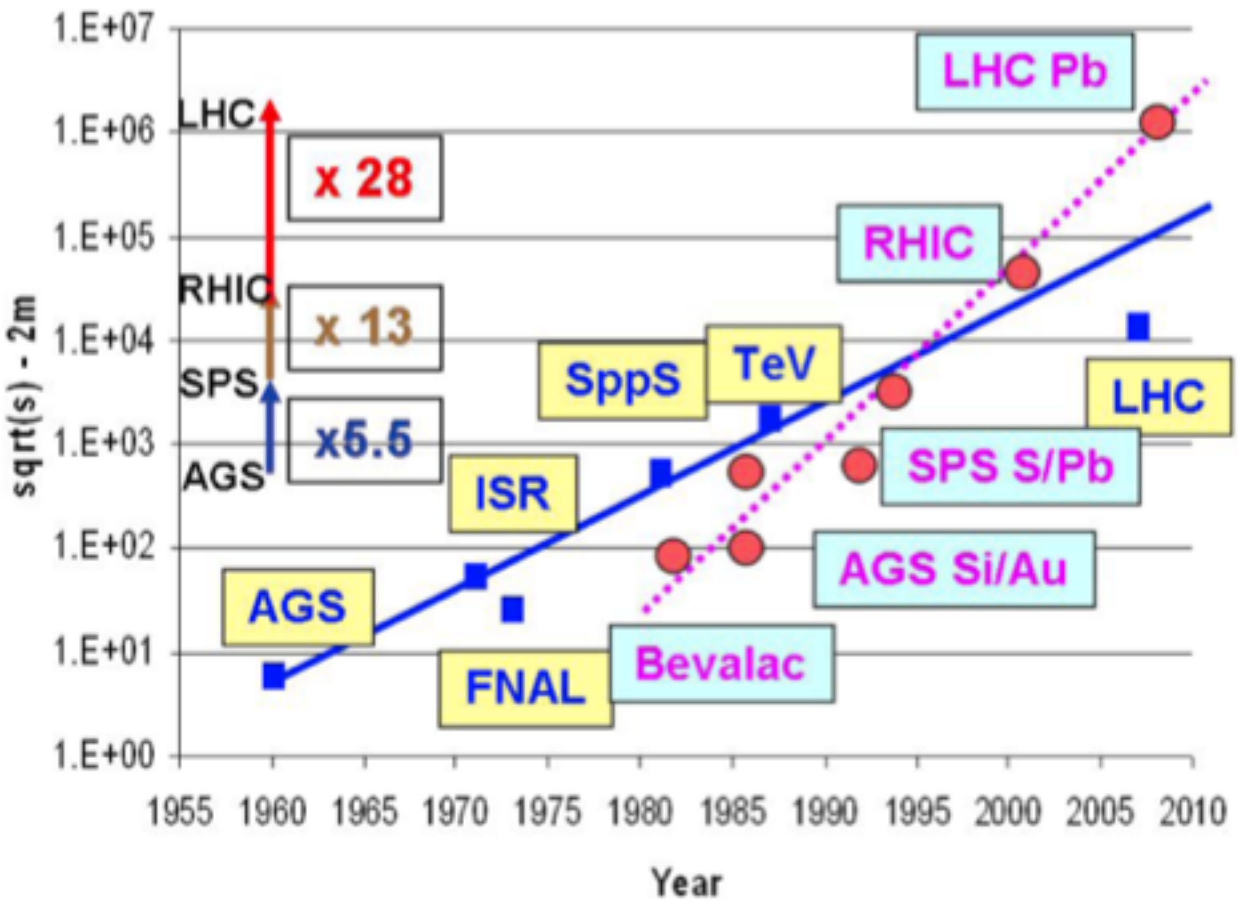
  - fixed target (1986-2003) $\sqrt{s}$ <20 GeV
- RHIC (BNL)
  - collider (2000-) $\sqrt{s}$ <200 GeV
- LHC (CERN)
  - collider (2008-) $\sqrt{s}$ <5500 GeV
- FAIR (GSI)
  - fixed target (2014-) $\sqrt{s}$ <9 GeV

Livingston plot

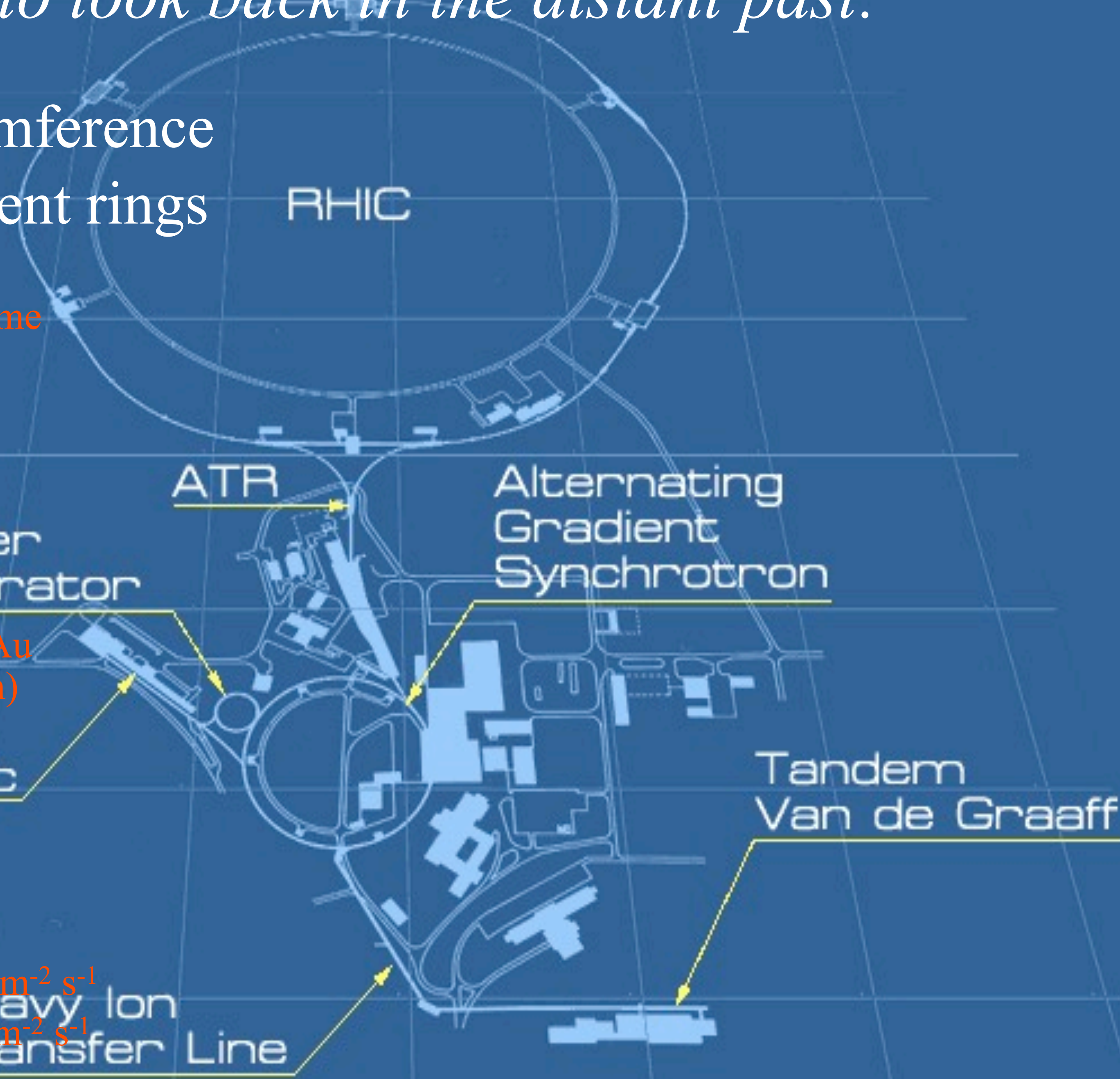


J. Schukraft, nucl-ex/0602014

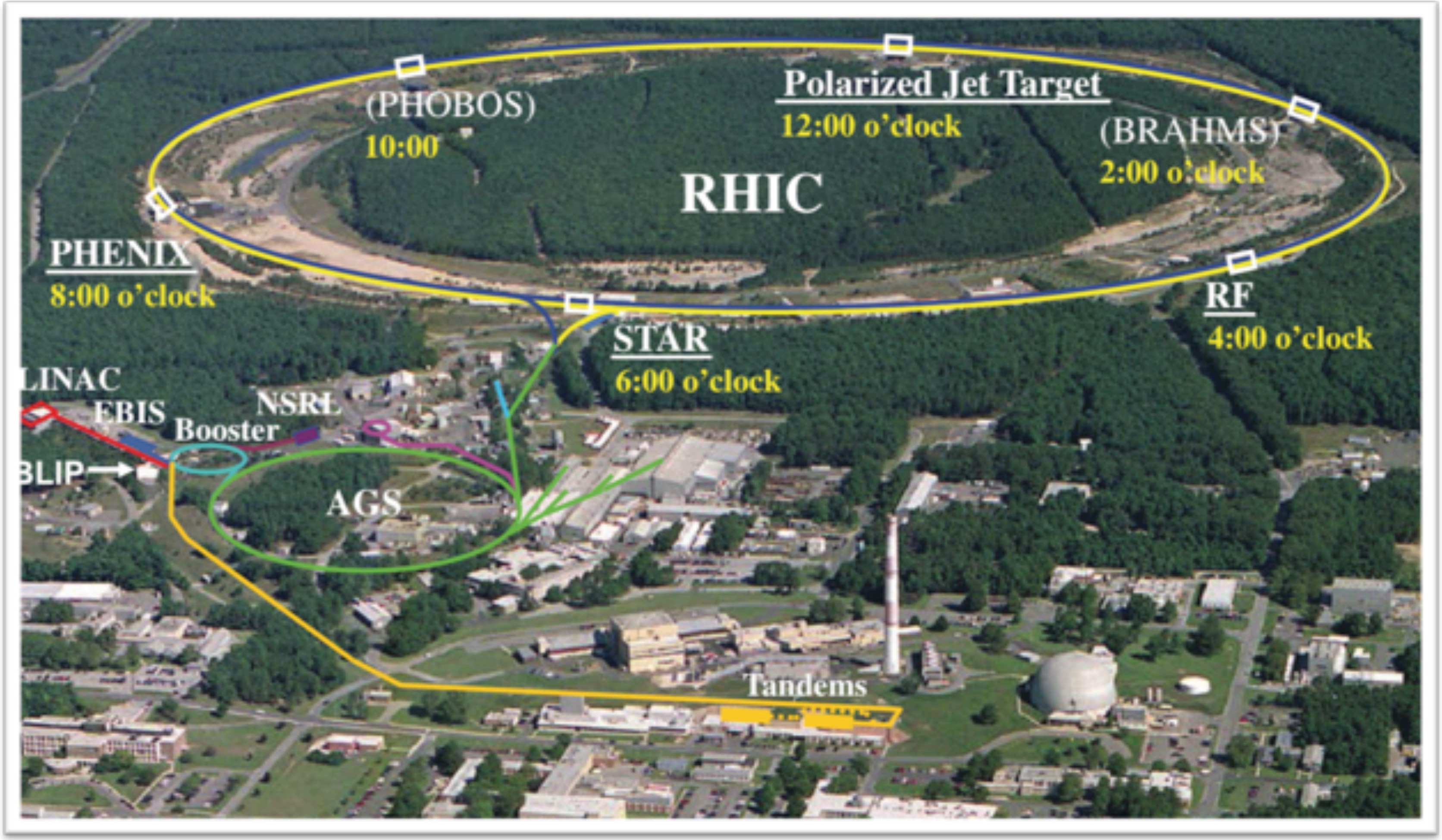
- Particle physics: doubling time ~every 4 years
- Heavy-Ion physics: doubling time ~ 1.7 years
  - Started in the 70's at the Bevalac, with a few dozen scientists, mostly from the US, Germany, Japan
- Energy increase ~ 10^4 in 25 years, leading to LHC
- >2000 physicists worldwide

How to look back in the distant past:

- 3.83 km circumference
- Two independent rings
  - 120 bunches/ring
  - 106 ns crossing time
- Capable of colliding
  ~any nuclear species
  on
  ~any other species
- Energy:
  - ➡ 200 GeV for Au-Au
    (per N-N collision)
  - ➡ 500 GeV for p-p
- Luminosity
  - Au-Au: 2 x 10^{26} cm^{-2} s^{-1}
  - p-p : 2 x 10^{32} cm^{-2} s^{-1}
    (*polarized*)



RHIC



(PHOBOS)
10:00
Polarized Jet Target
12:00 o'clock
(BRAHMS)
2:00 o'clock
RHIC
PHENIX
8:00 o'clock
RF
4:00 o'clock
STAR
6:00 o'clock
LINAC
EBIS
NSRL
Booster
BLIP
AGS
Tandems

RHIC: new physics and many surprises!

- The (unreasonable?) success of hydrodynamics
  - Matter flows like a liquid
  - Specific viscosity is ***very*** low (almost 0)
    - A connection with other strongly coupled systems:
      - » Cold fermionic atoms
      - » String theory (!)
  - System is strongly coupled
- Matter is surprisingly opaque
  - Jets are quenched by the strongly interacting system
- Electromagnetic signals

Relativistic hydrodynamics works!

…Relativistic hydrodynamics?!?

$$\boxed{T^{\mu\nu} = (e+P)u^\mu u^\nu - Pg^{\mu\nu}}$$ (ideal hydro)

$$u = (\gamma, \gamma \vec{\mathrm{v}})$$

In a frame where the fluid is locally at rest:

$$\boxed{u = (1,0,0,0), \quad T^{00} = e, \quad T^{ij} = P\delta^{ij}, \quad T^{i0} = 0}$$

Conservation of energy & momentum:

$\partial_\mu T^{\mu\nu} = 0$ 4 equations, 5 unknowns: $e, P, u^\mu \ (u^2 = 1)$

$\boxed{\text{EoS: } \mathrm{P}=f\,(\mathrm{T}, n)}$ ← *Where our knowledge of QCD enters*

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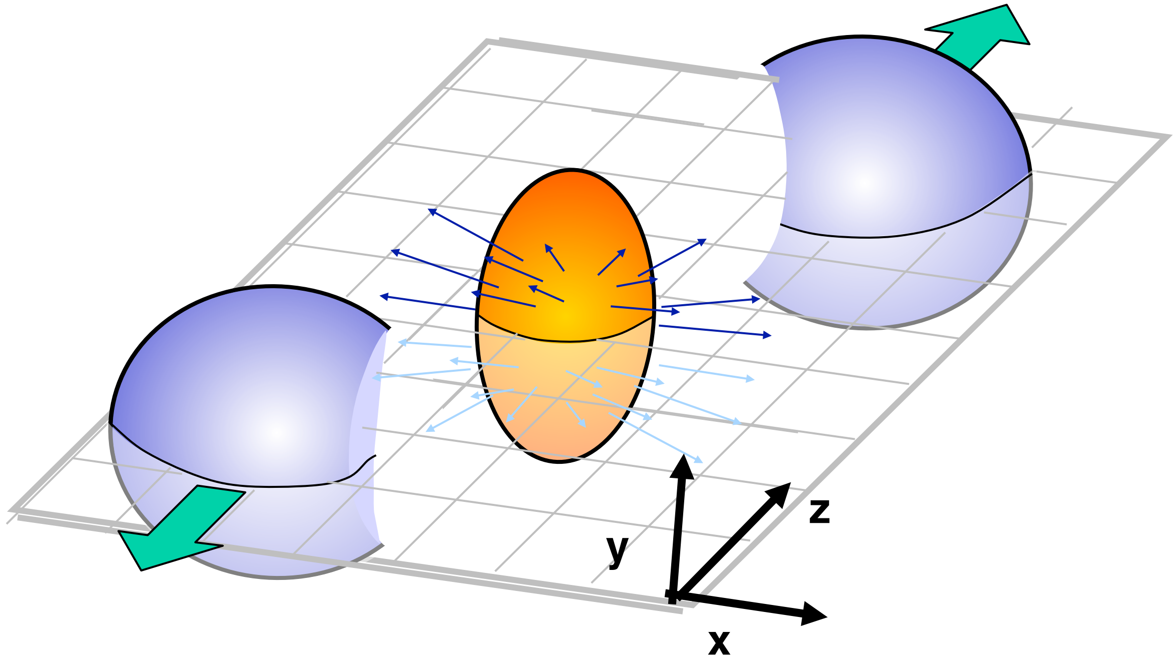
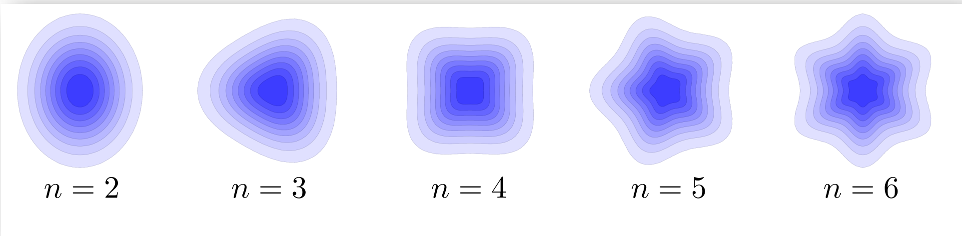
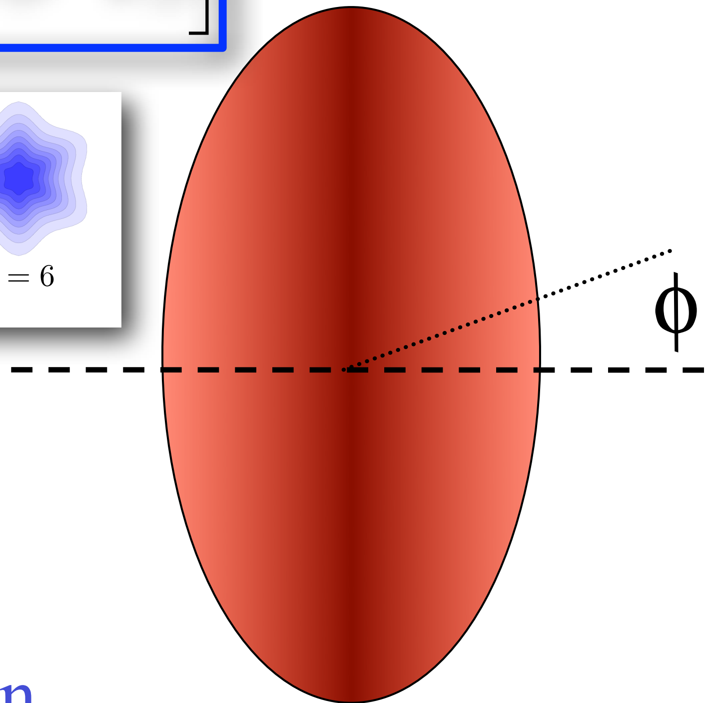
A surprise from RHIC:
Matter flows like a liquid!



A surprise from RHIC:
Matter flows like a liquid!

$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{p_T dp_T d\phi}\left[1+\sum_n 2v_n \cos n(\phi-\psi_n)\right]$$





Positive v2 = in plane emission
Negative v2 = out of plane emission

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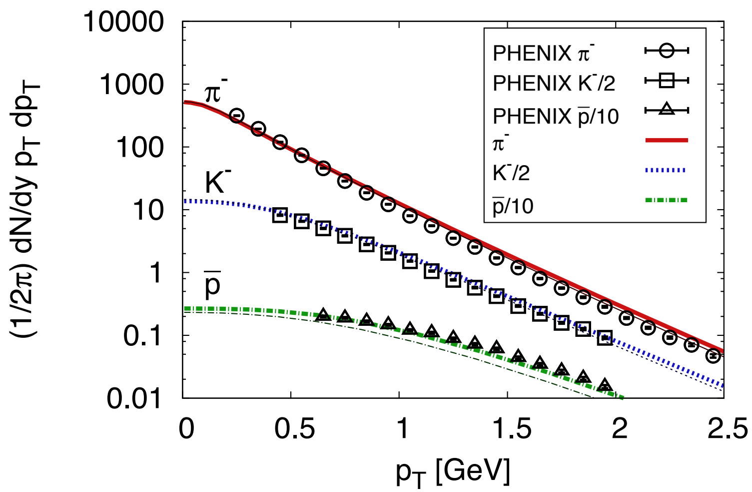
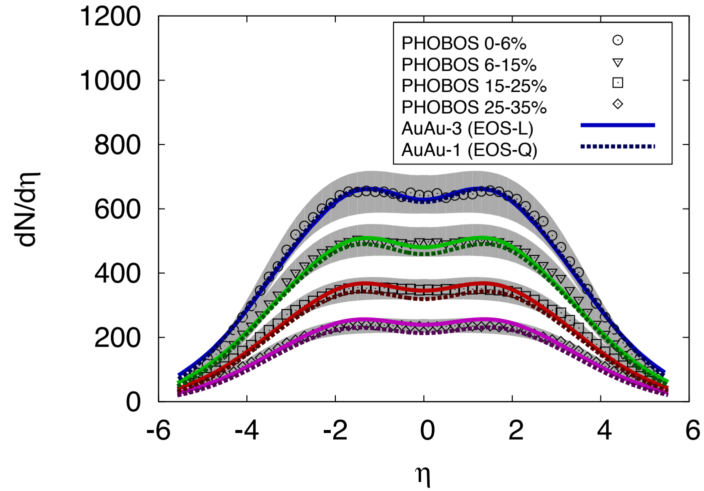
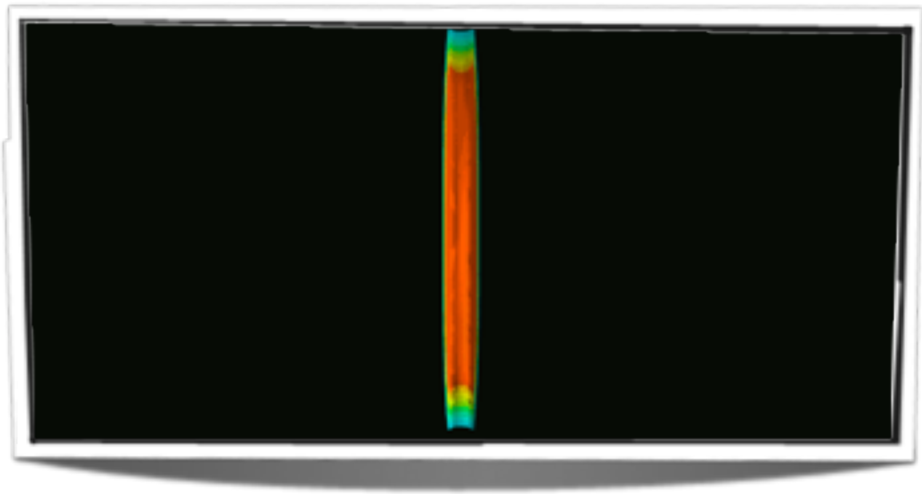
Hydro performance





- Address all data in the soft sector with one consistent approach
- Needs a rapid thermalization

MUSIC



(Animation: B. Schenke)

Schenke, Jeon, Gale PRC 2010

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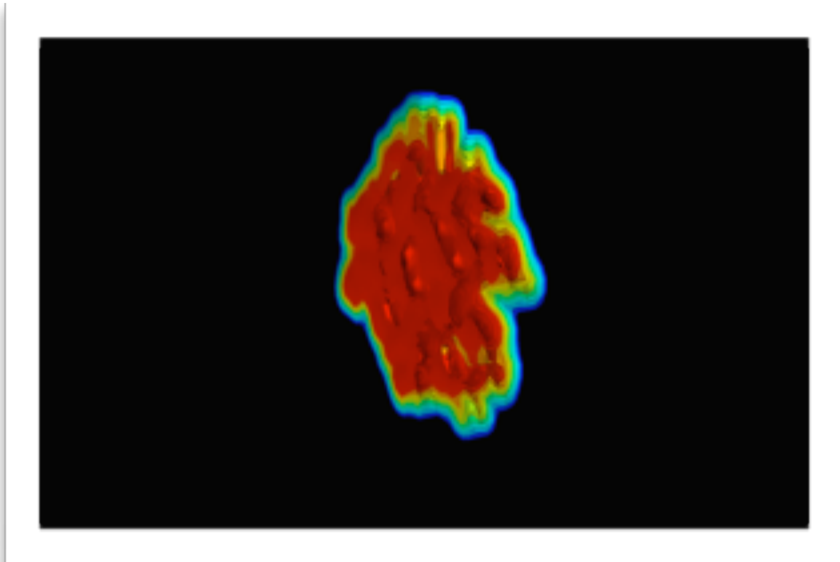
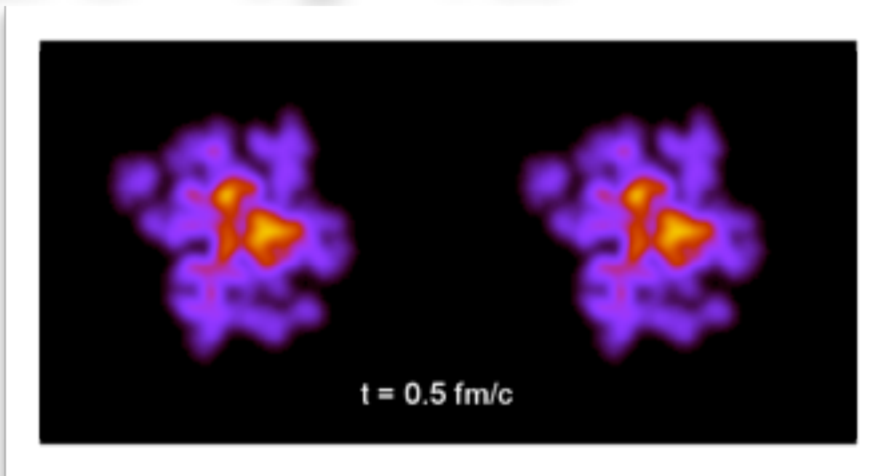
Hydro calculations moving closer and closer to genuine ab-initio, 3+1D, with finite shear viscosity !



Lumpy initial states Au + Au @RHIC

Viscosity, A clear effect:

$$T^{\mu\nu} = (\epsilon + P)u^{\mu}u^{\nu} - Pg^{\mu\nu} + \Pi^{\mu\nu}$$



$$\eta / s = 2 / 4\pi$$

(Animations: B. Schenke)

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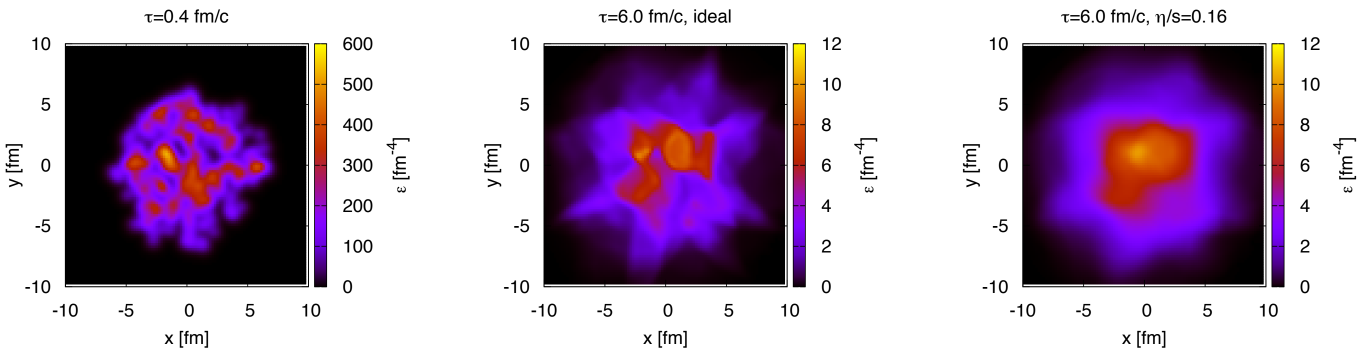
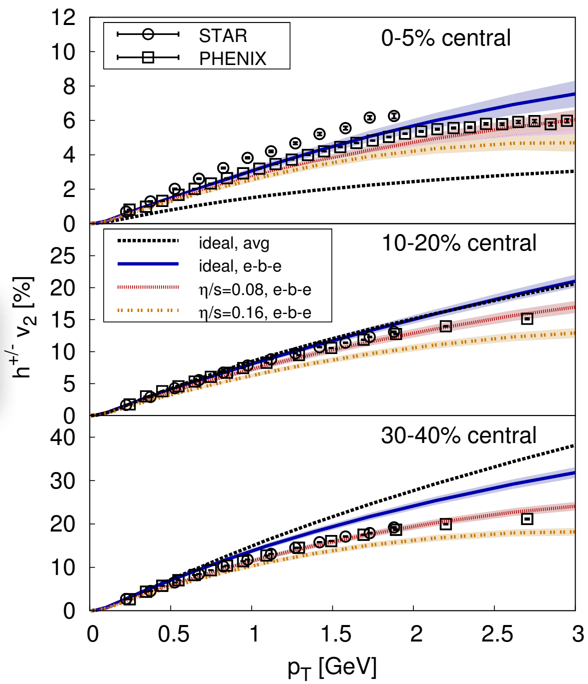
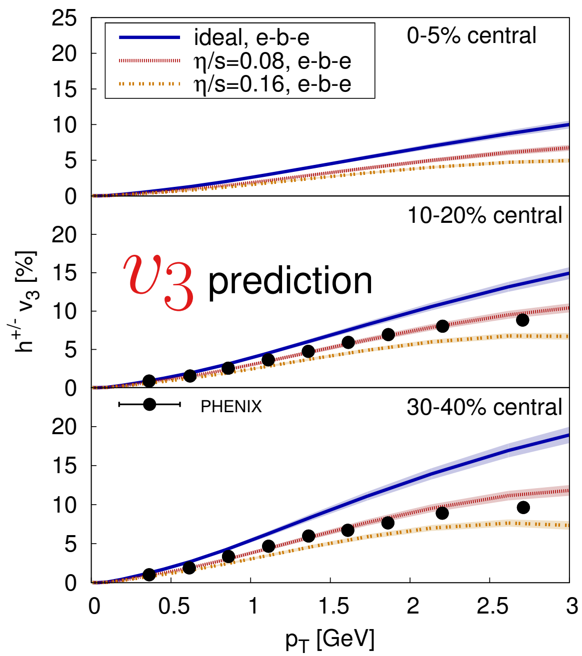
How do we know the nature of the initial state?



$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{p_T dp_T d\phi}\left[1+\sum_n 2v_n \cos n(\phi-\psi_n)\right]$$

$$(v_{\mathrm{odd}})_{\mathrm{smooth}} \equiv 0$$





Schenke, Jeon, Gale, PRL (2011)

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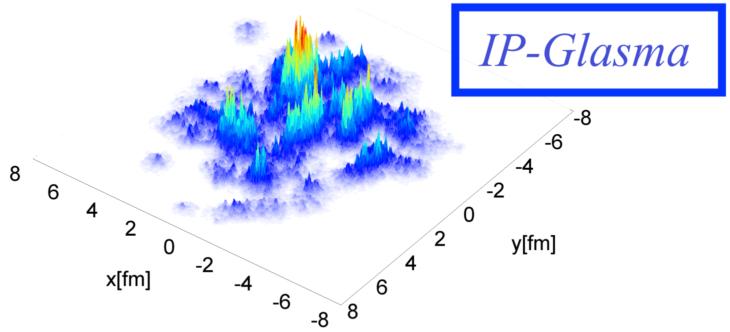
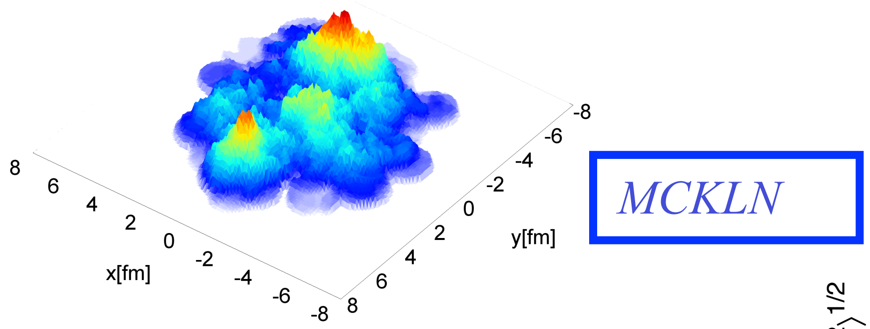
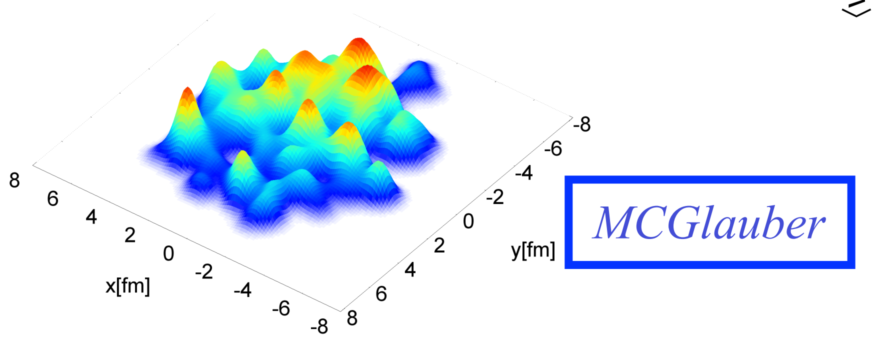
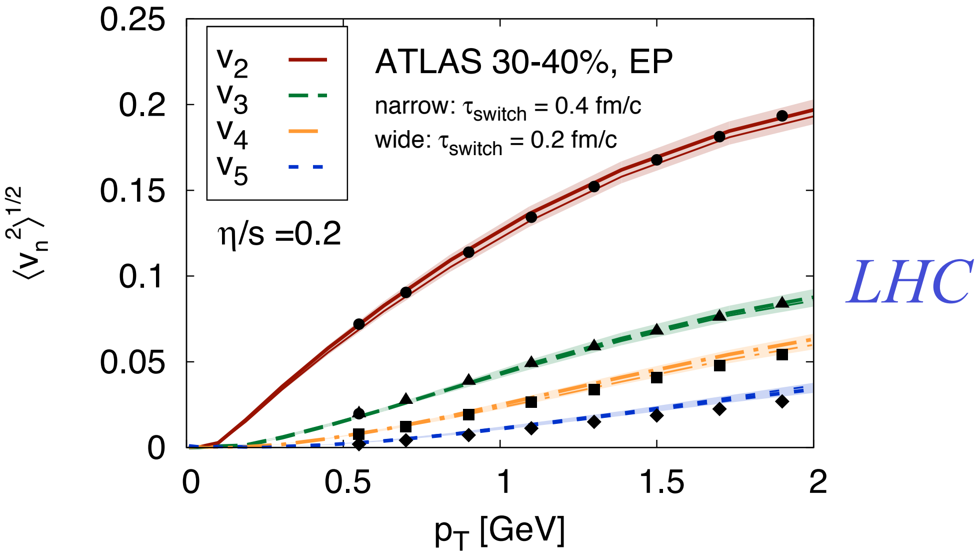
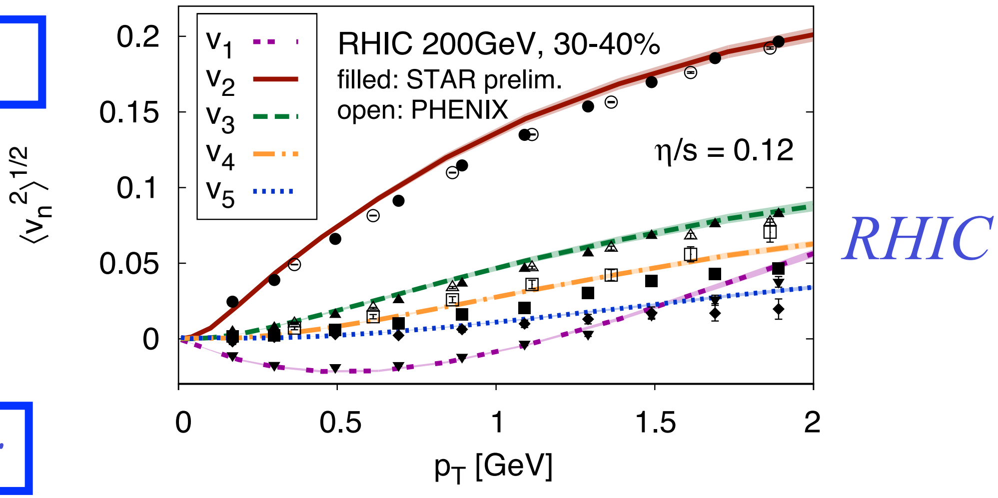
Closing in on the initial state





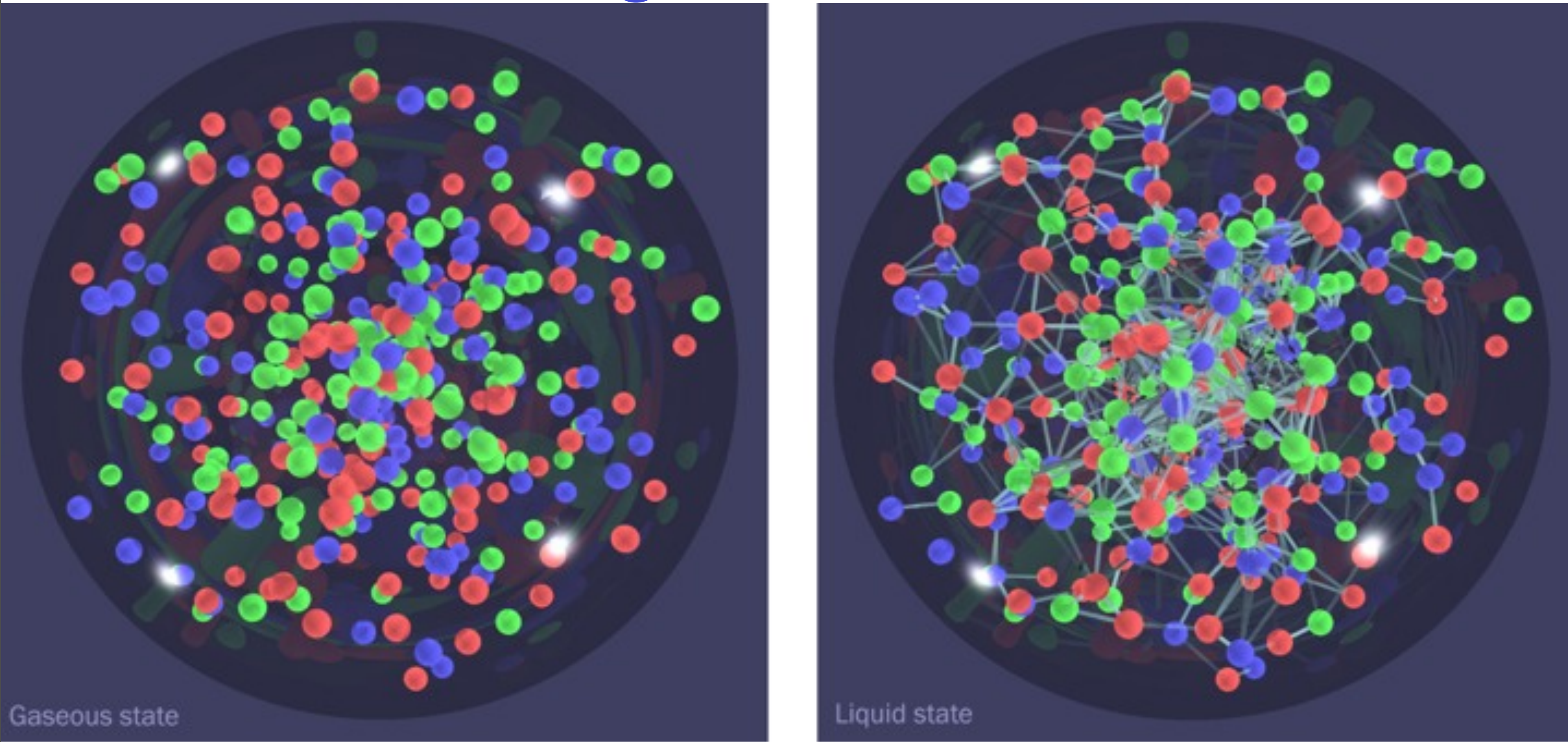






Schenke, Tribedy, Venugopalan, PRL 2012
Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 2012

The plasma is liquid-like, rather than gas-like…

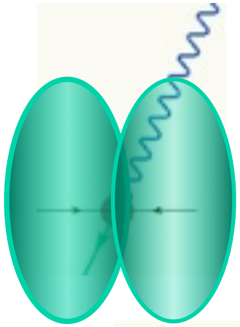


…and RHIC can measure the viscosity!

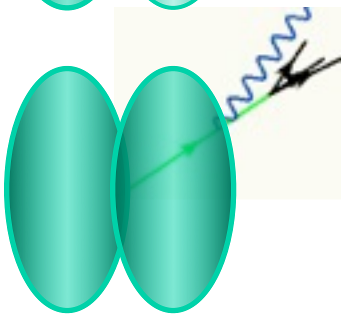
The role played by electromagnetic radiation

- Penetrating probes: negligible final state effects (α)
- Real and virtual photons are complementary
- Thermal photon emission is from hotter zones of the colliding system
- Emitted throughout the collision history
- Low emission rates
- Procedure: Calculate thermal emission rates & use hydrodynamics to model the evolution. Integrate rates over whole history

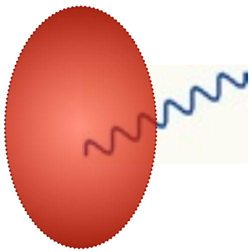
Sources of photons
in a relativistic nuclear collision:



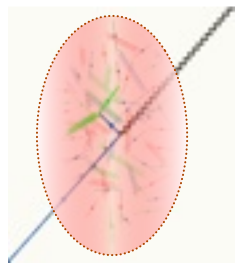
Hard direct photons. pQCD with shadowing
Non-thermal



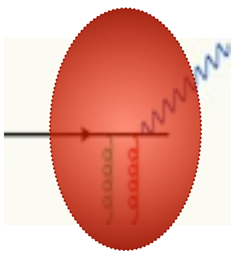
Fragmentation photons. pQCD with shadowing
Non-thermal



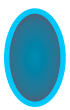
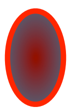
Thermal photons
Thermal



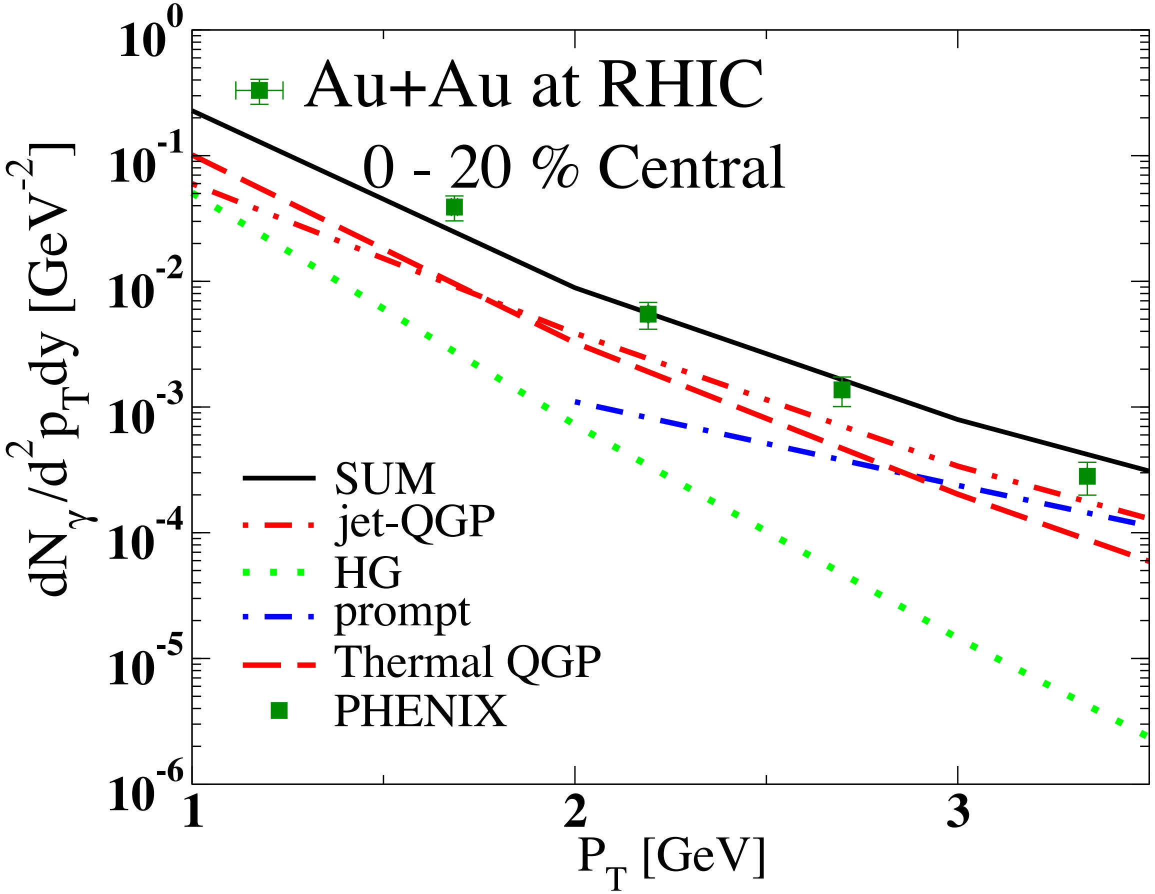
Jet-plasma photons
Thermal



Jet in-medium bremsstrahlung
Thermal

 Pre-equilibrium? 

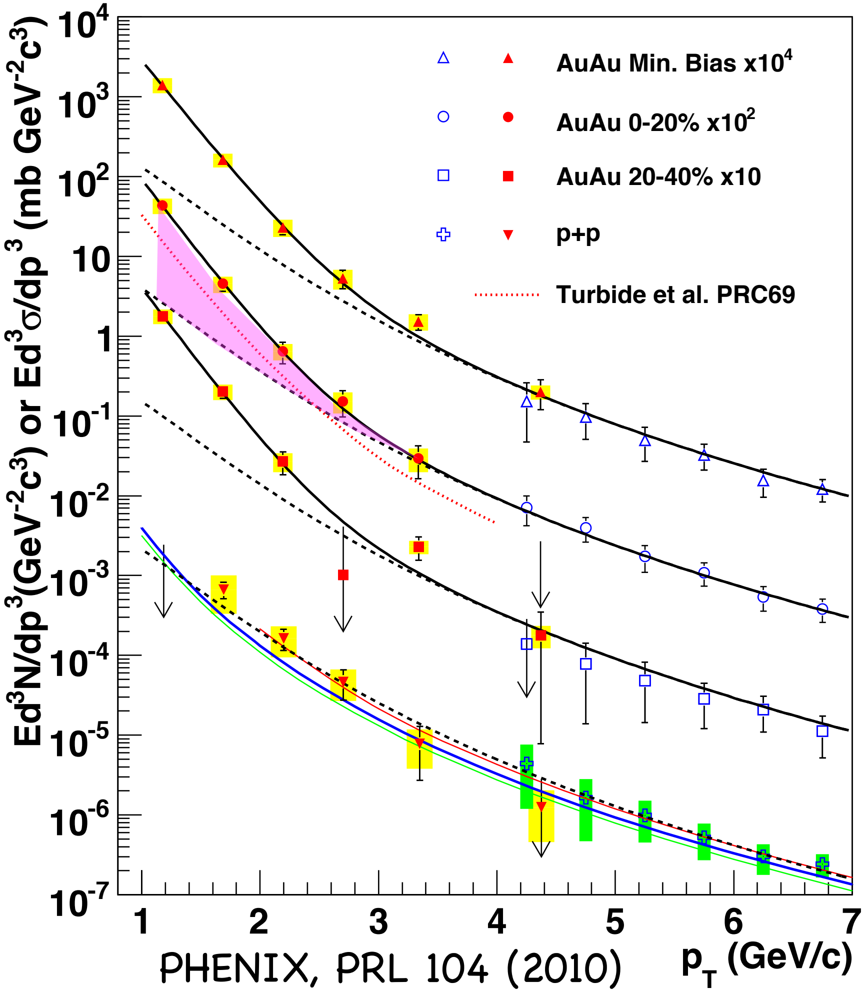
Applying this to interpret photons measured @ RHIC: Rates are integrated using relativistic hydrodynamic modeling



- At low p_T, spectrum dominated by thermal components (HG, QGP)
- At high p_T, spectrum dominated by pQCD
- Window for jet-QPG contributions at mid-p_T

Turbide, Gale, Frodermann, Heinz, PRC (2008);
Higher p_T: G. Qin et al., PRC (2009)

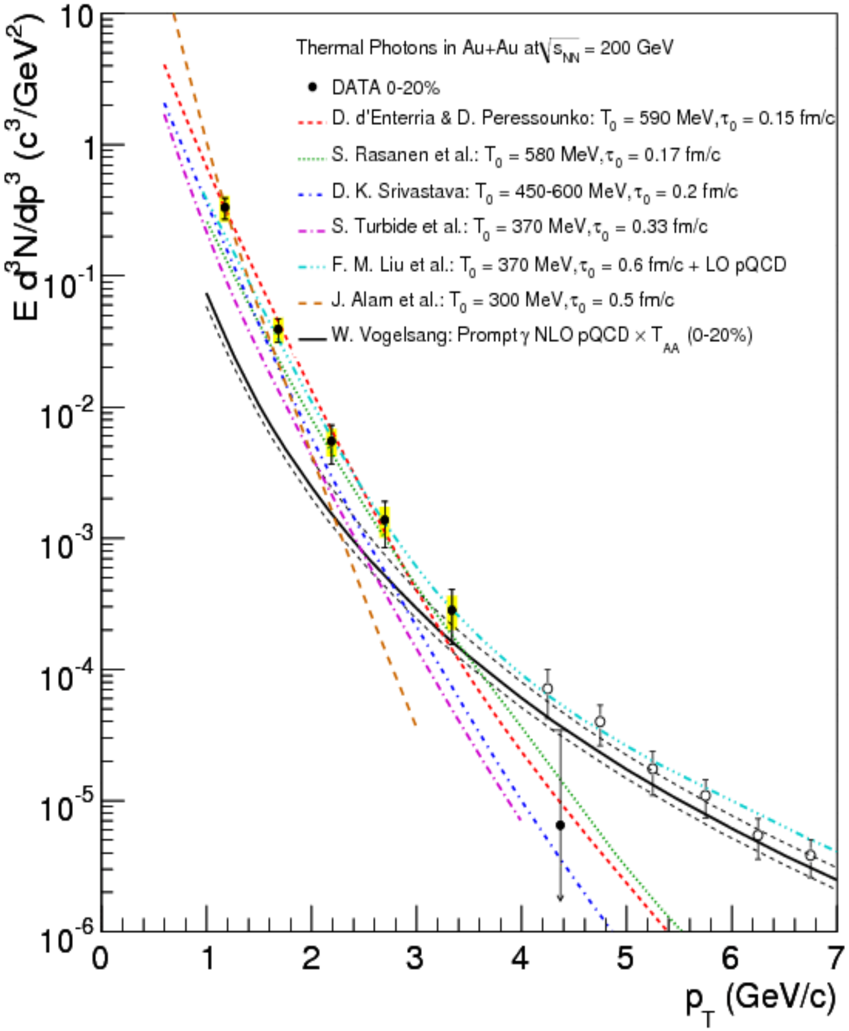
One of the uses of photons: Characterizing the hot matter created at RHIC



PHENIX, PRL 104 (2010)

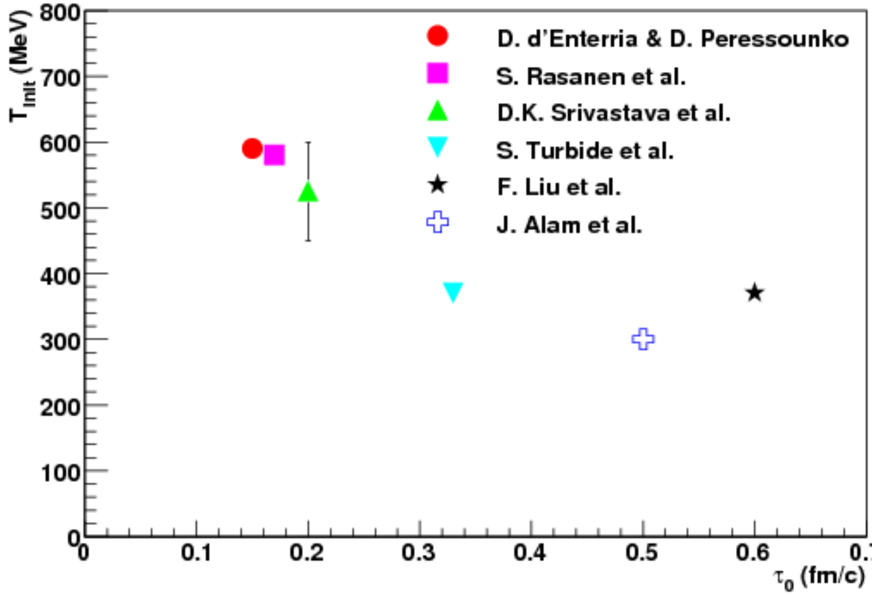
$$T_{\text{excess}} = 221 \pm 19 \pm 19\,\text{MeV}$$

One of the uses of photons: Characterizing the hot matter created at RHIC



D'Enteria & Peressounko, Eur. Phys. J. (2006)

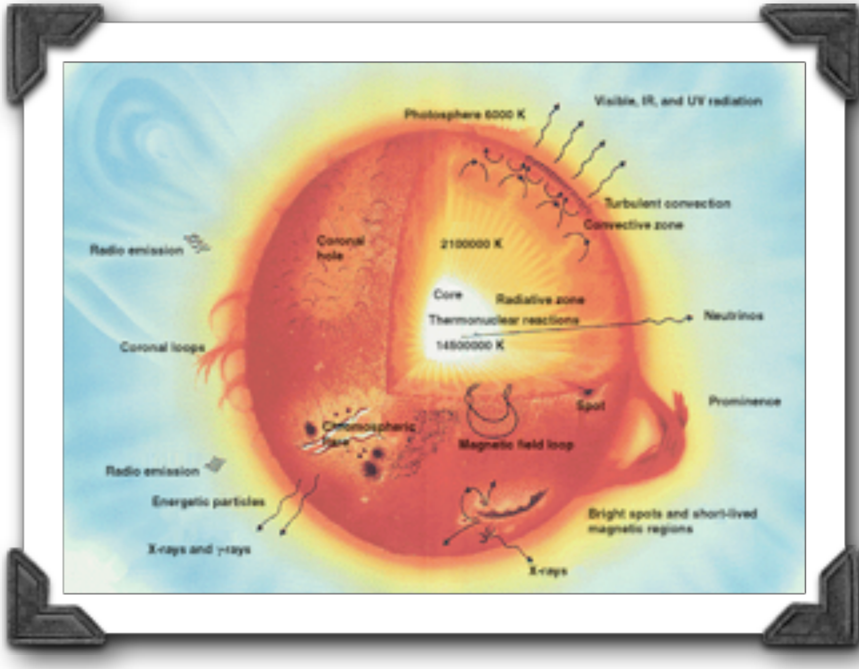
$$T_{excess} = 221 \pm 19 \pm 19\,\text{MeV}$$



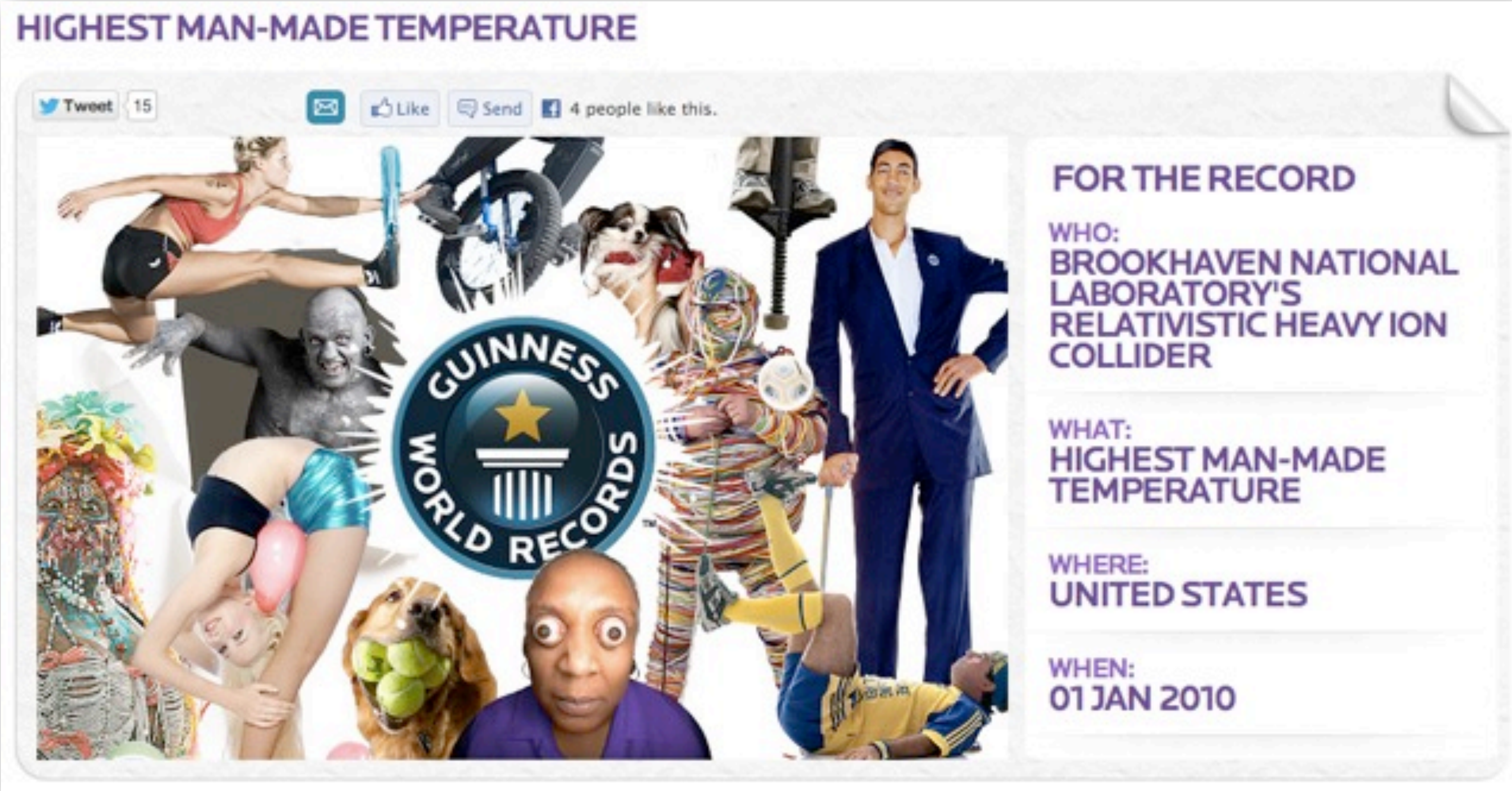
T_{ini} = 300 to 600 MeV
t_0 = 0.15 to 0.5 fm/c

RHIC AS A THERMOMETER

- 500 MeV = 5.8 x 10^{12} °K – Hotter than the sun (~15-20 x 10^{6} °K)

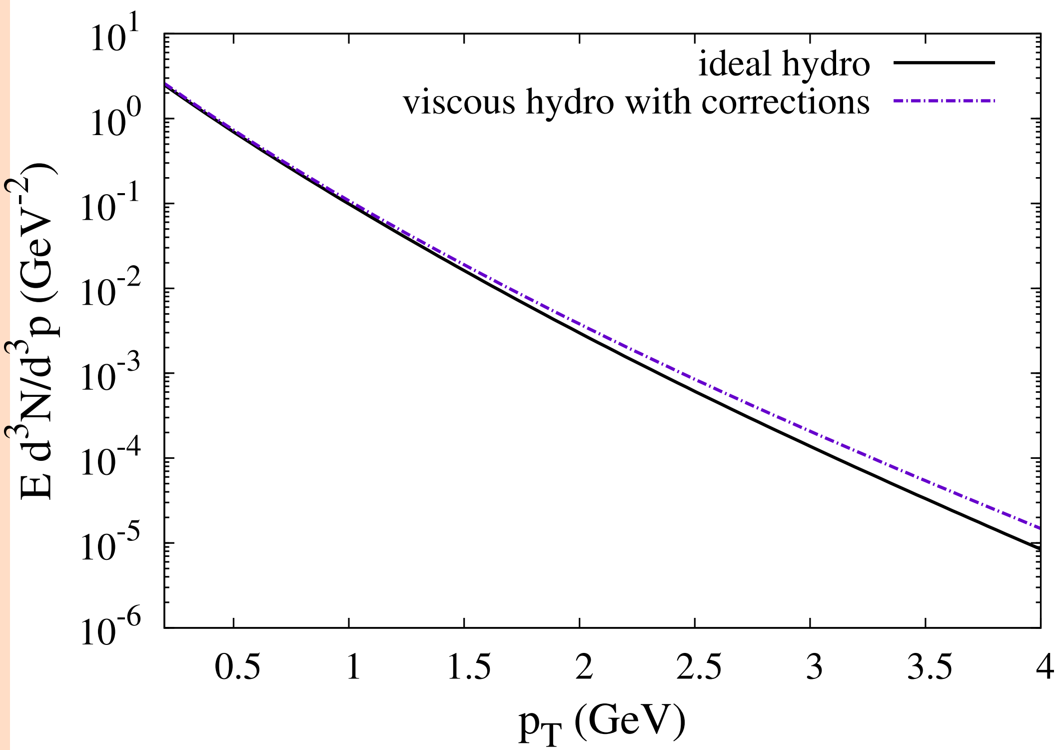


RHIC AS A THERMOMETER



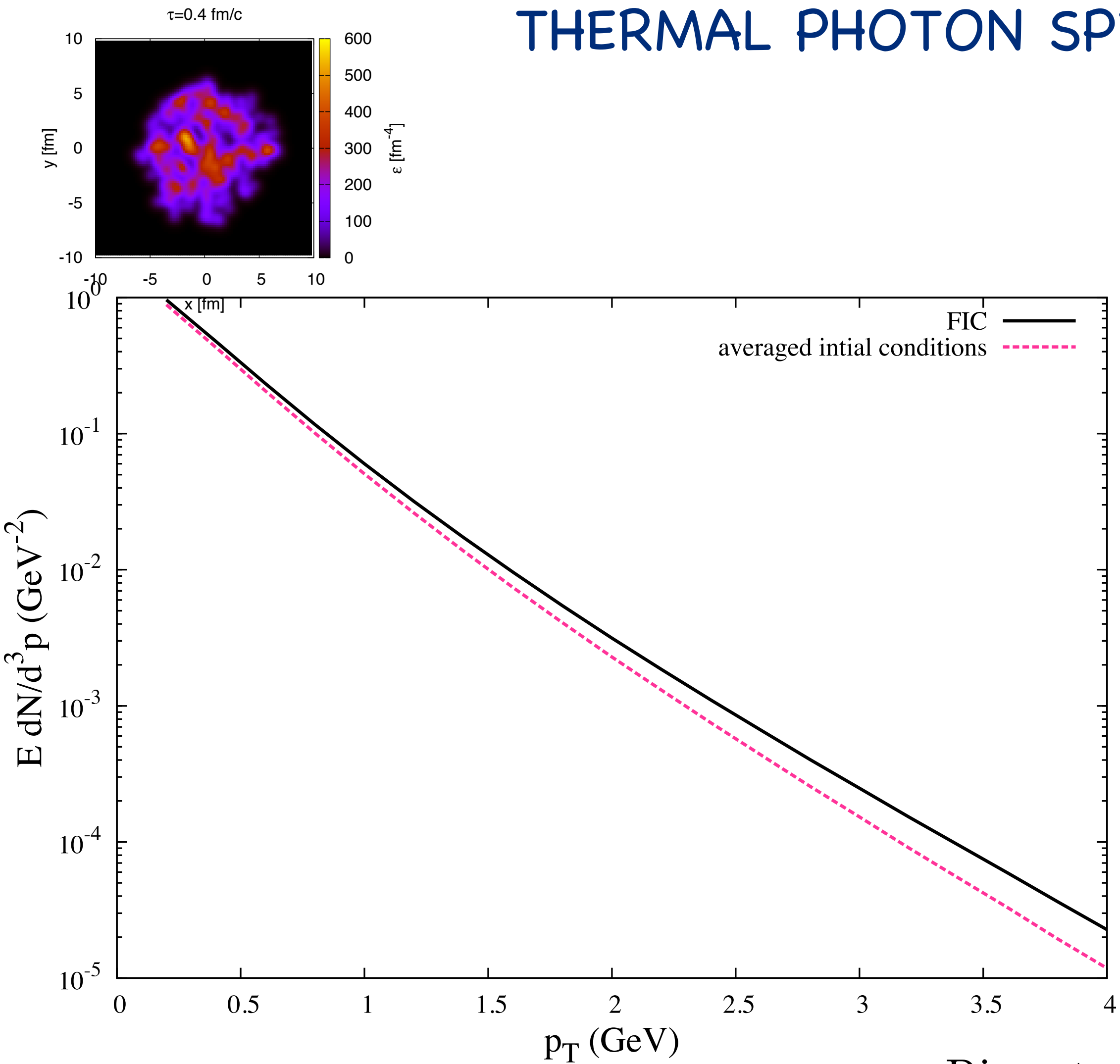
Recently calculated Effects: (1) Shear viscosity on the net thermal photon yield

$$f_H \rightarrow f_H + \delta f_H$$



- Viscous corrections make the spectrum harder, ≈100% at p_T = 4 GeV.
- Increase in the slope of ≈15% at p_T = 2 GeV.
- Extracting the viscosity from the photon spectra will be challenging
- Once pQCD photons are included: a few % effect from viscosity
- More work is still needed to properly include all photon sources in a consistent way

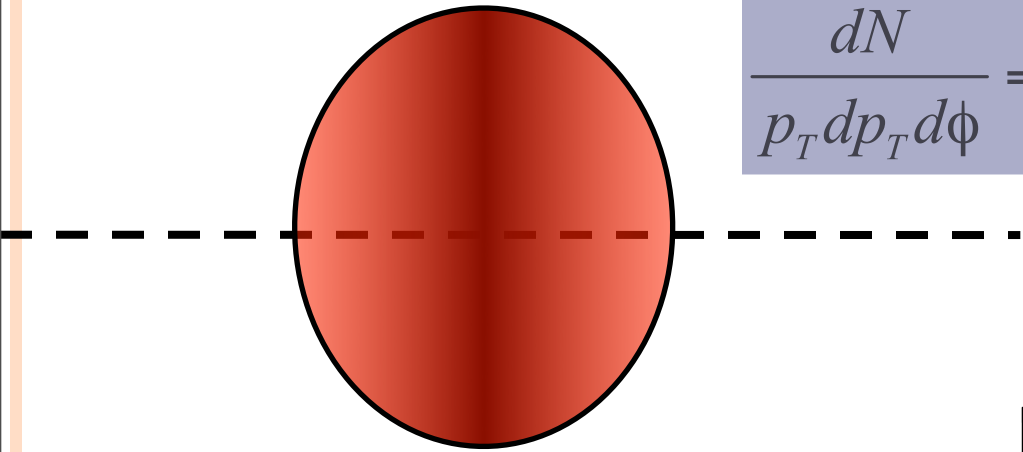
Recently calculated effects: (2) FIC on the thermal photon spectrum



- FIC produces higher initial T (hot spots), and higher initial gradients
- FIC conditions are demanded by hadronic data (v_{odd})
- These lead to a harder spectrum, *as for hadrons*

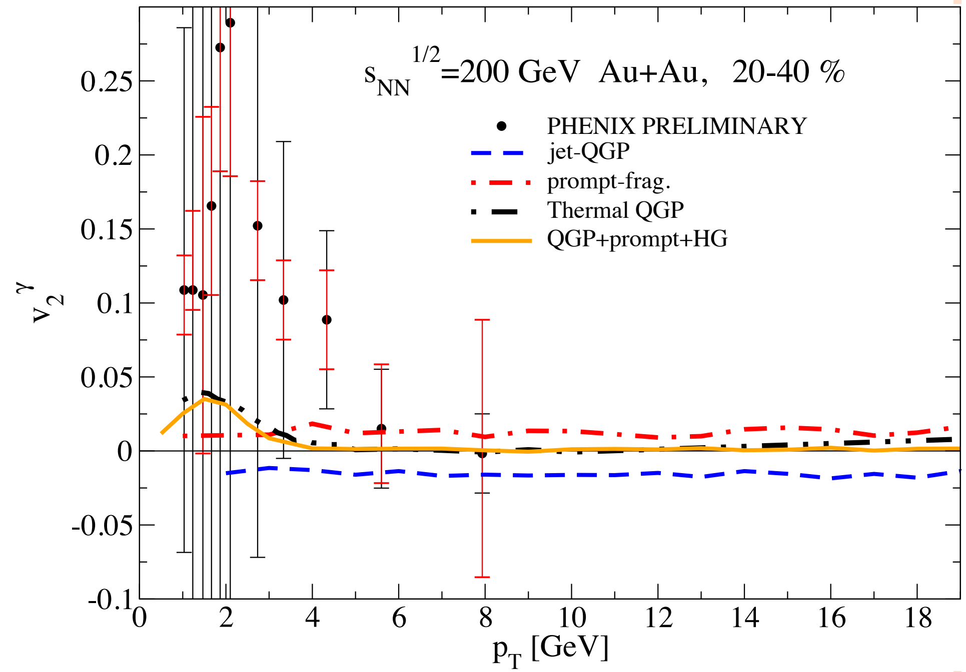
Dion et al., PRC (2011)
Chatterjee et al., PRC (2011)

BEYOND SIMPLE SPECTRA: FLOW AND CORRELATIONS



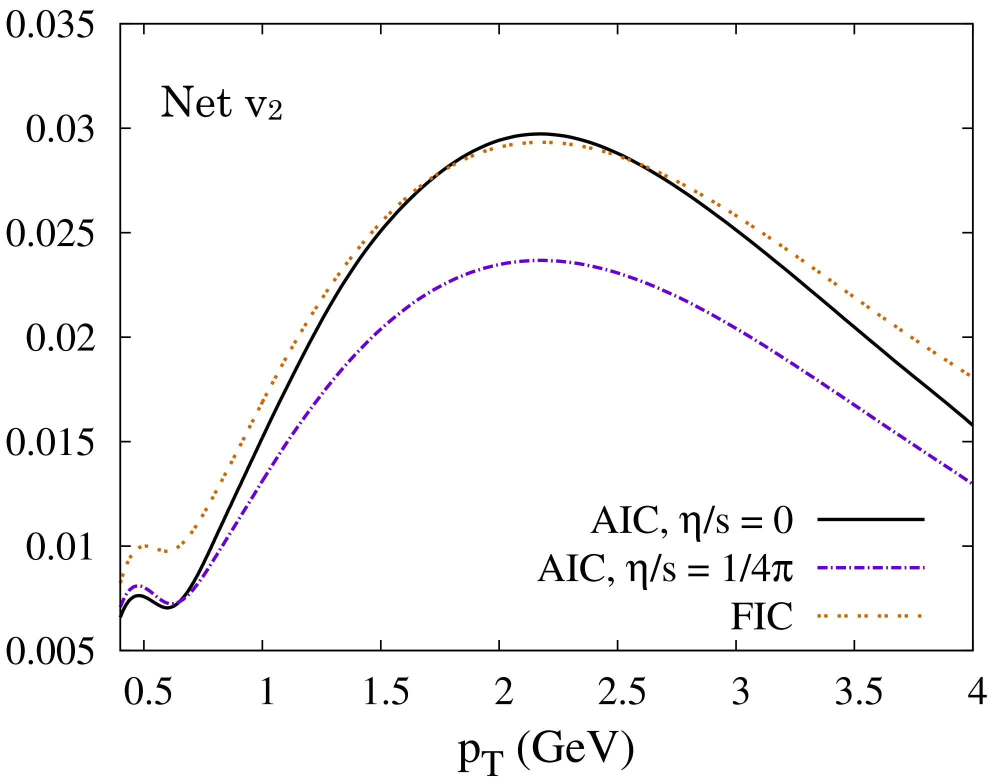
$$\frac{dN}{p_T dp_T d\phi} = \frac{dN}{2\pi\, p_T dp_T}\left[1 + \sum_n 2v_n \cos(n\phi)\right]$$

- Soft photons will go with the flow
- Jet-plasma photons: a negative v_2
- Details will matter: flow, T(t). . .



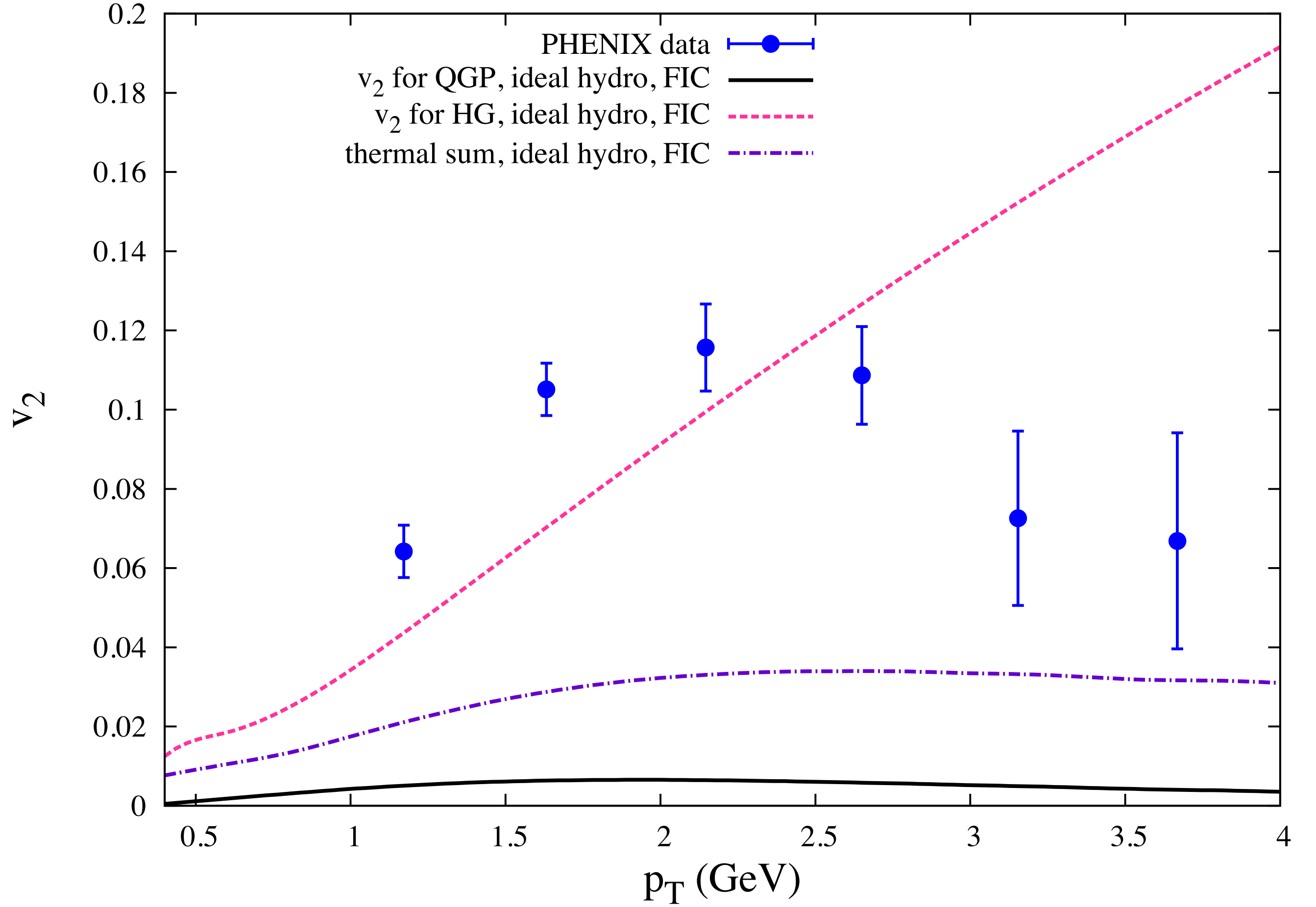
Turbide, Gale, Fries PRL (2006)
Low p_T: Chatterjee *et al.*, PRL (2006)
All p_T: Turbide *et al.*, PRC (2008)

Theory: Net thermal photon v_2



- FICs enhance v_2 in this centrality class (0-20%), as for hadrons
- Viscous effects decrease v_2
- Net v_2 is comparable in size to that with ideal medium
- There is new RHIC data

RHIC Photon v_2 Data



- New data is higher than calculation, even with e-b-e initial state fluctuations, and ideal hydro
- Size comparable with HG v_2

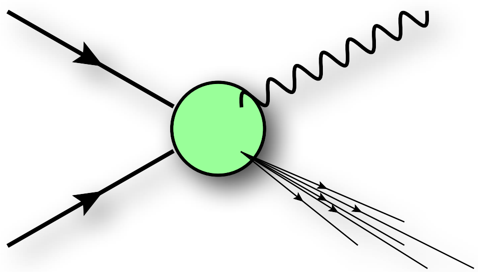
PUZZLE!

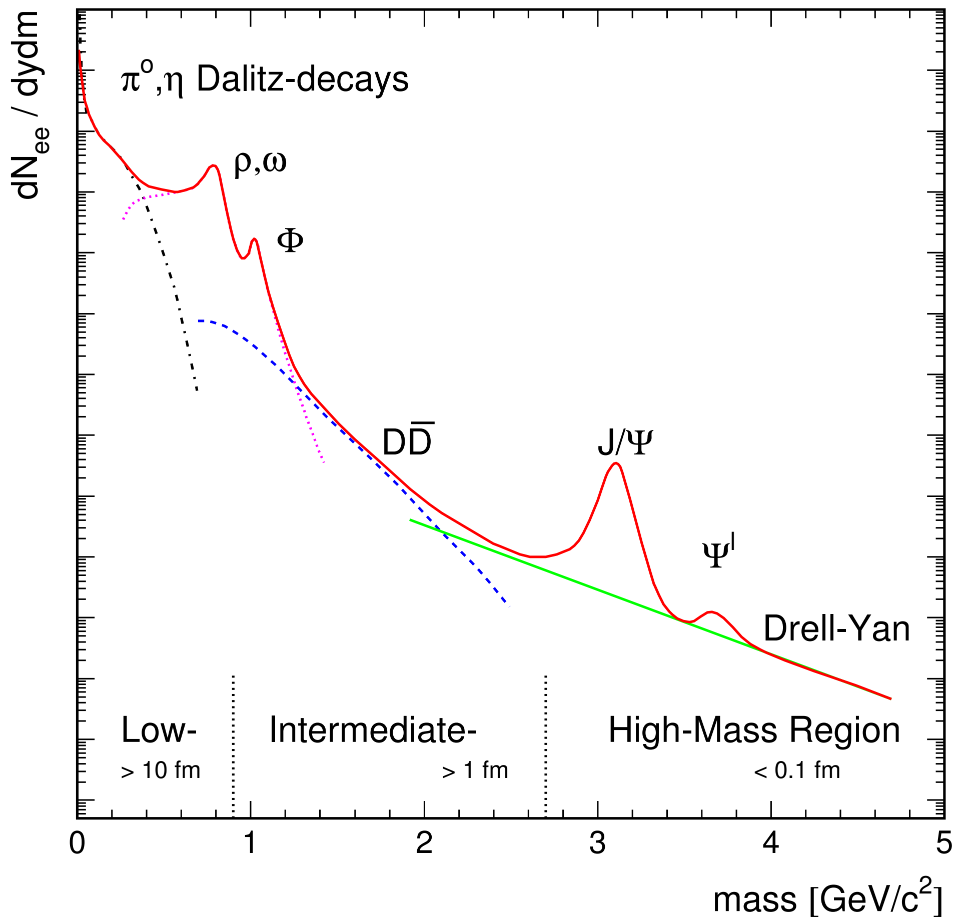
Some facts and some leads

- FICs are here to stay. The meaning of "initial temperature" is altered.
- Need to explore hydro initialization and parameters. This requires consistency with the hadronic data.
- Making the QGP signal larger will *decrease* the v_2. Including the T=0 photons, will *decrease* v_2.
- Non-zero initial shear tensor? Primordial flow?
- Some ideas from the pre-equilibrium era of the evolution

What about dileptons?

Thermal dilepton spectrum, and elliptic flow





Picture: A. Drees

- Additional degree of freedom: M and p_T may be varied independently
- Same strategy: calculates rates, use hydro

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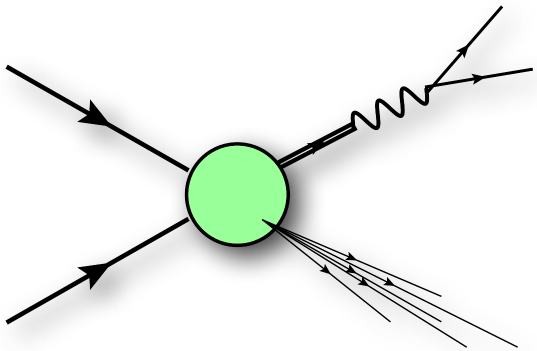
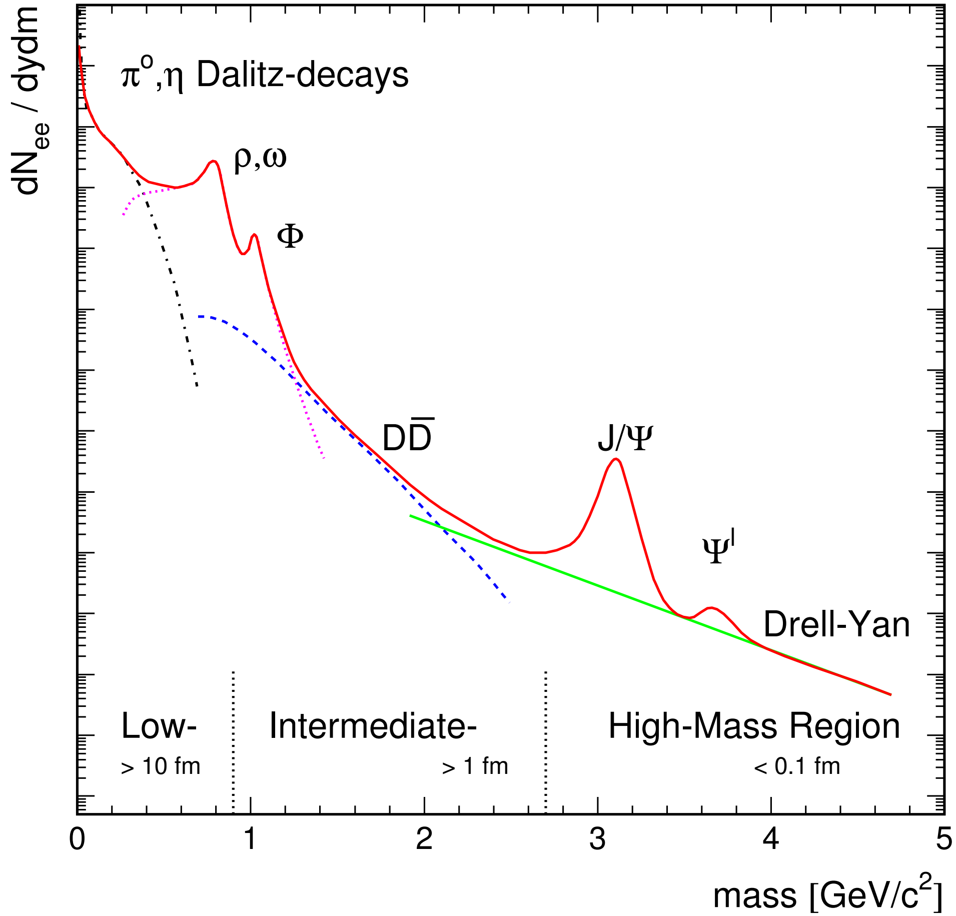
Thermal dilepton spectrum, and elliptic flow





Picture: A. Drees

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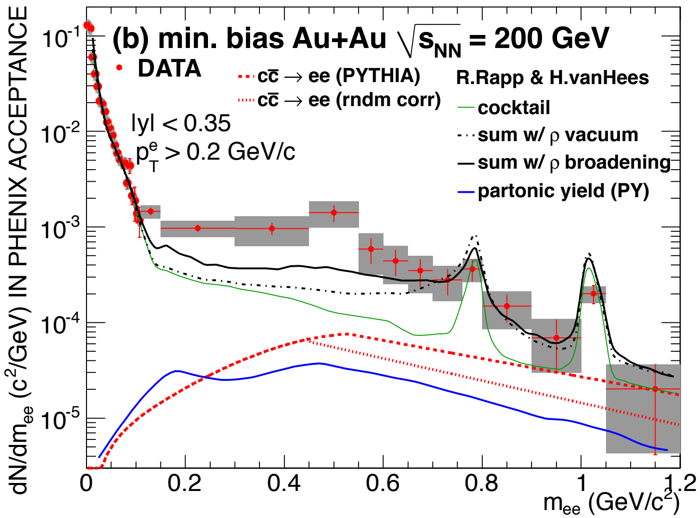
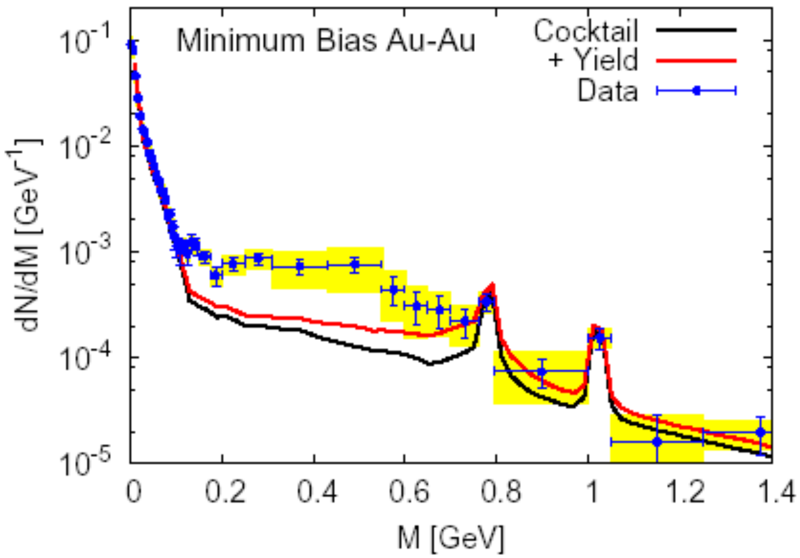
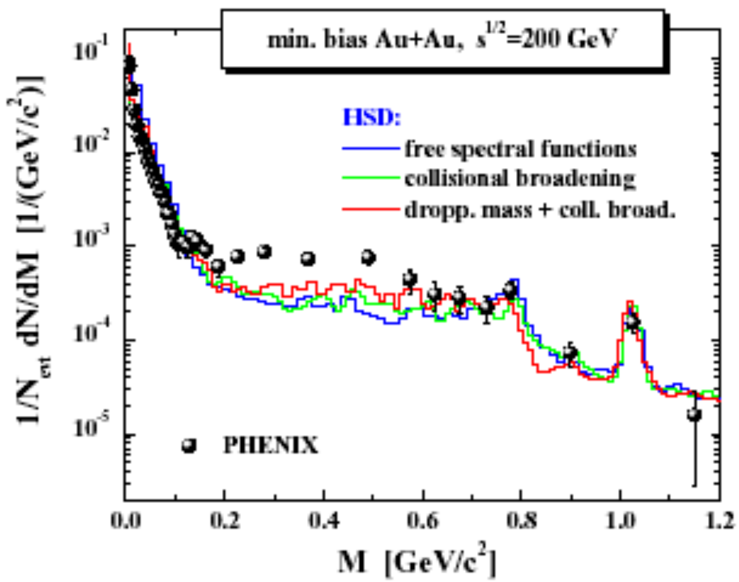
DILEPTONS, THE STORY AS OF A FEW MONTHS AGO



van Hees, Rapp (2010)

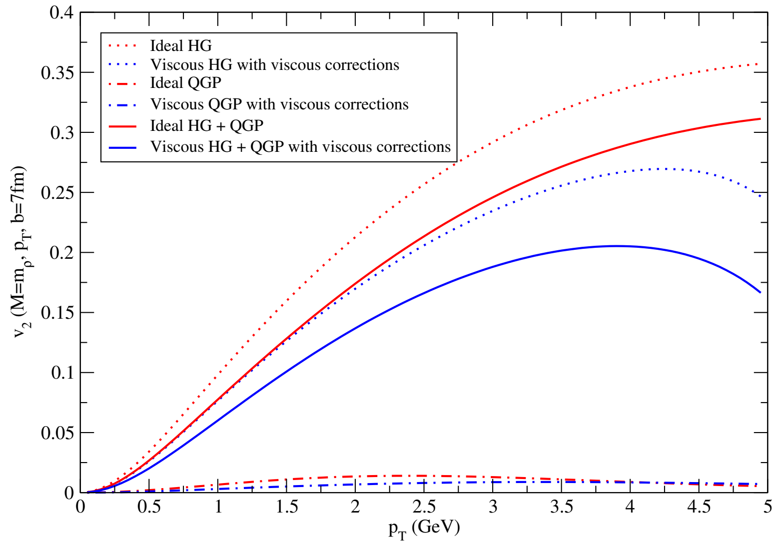


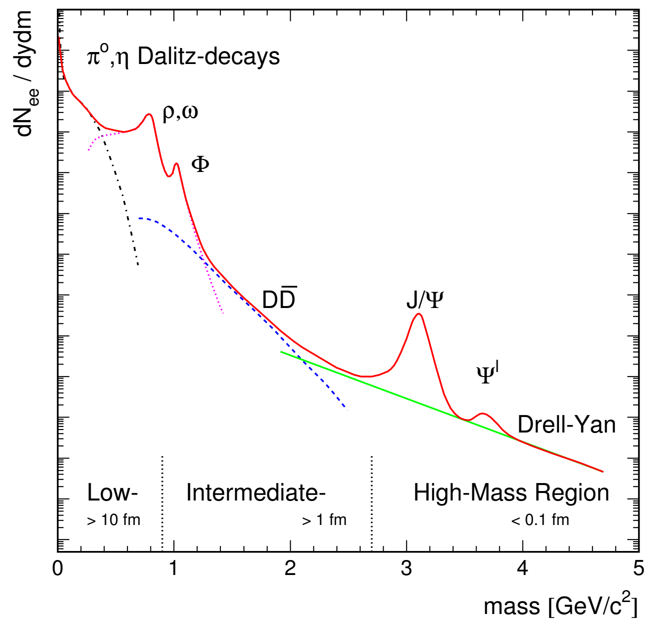
Dusling, Zahed (2009)

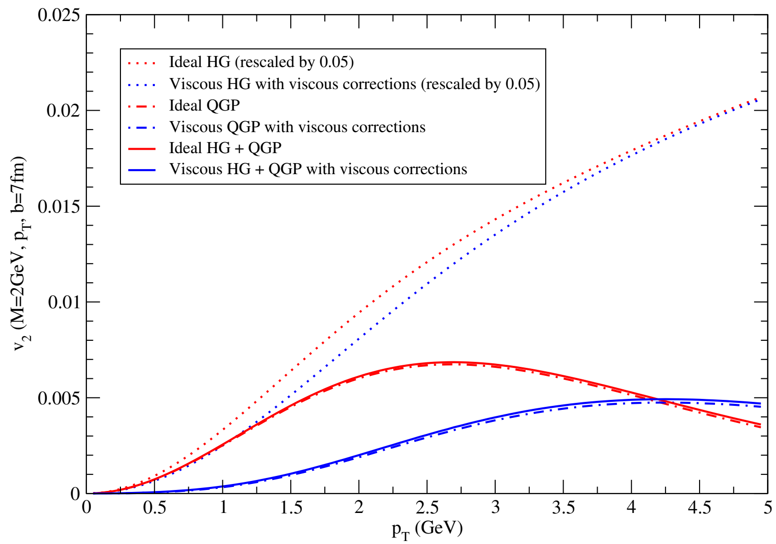


Bratkovskaya, Cassing, Linnyk (2012)

THERMAL DILEPTON V2 WITH VISCOUS EFFECTS



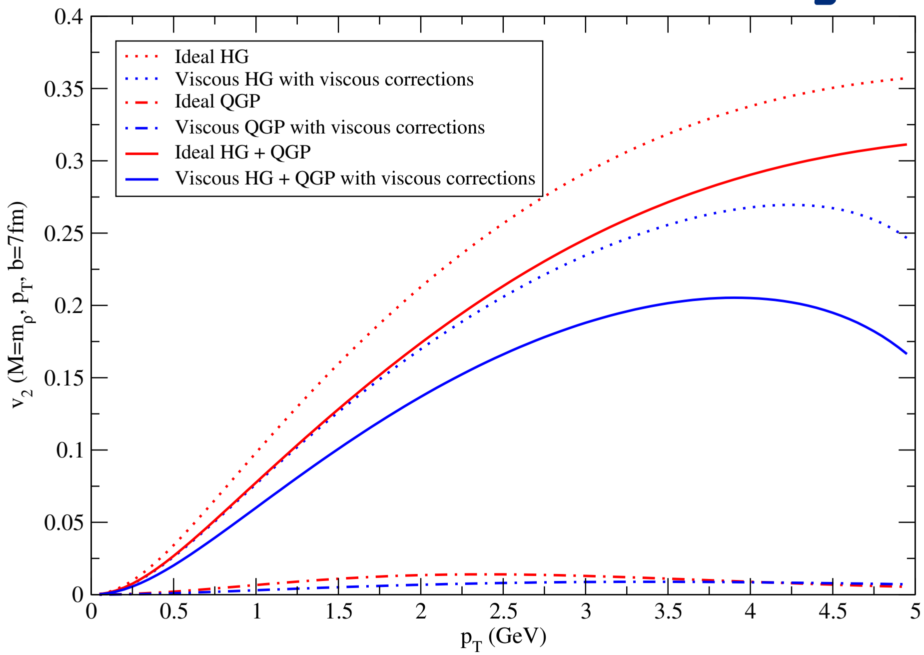


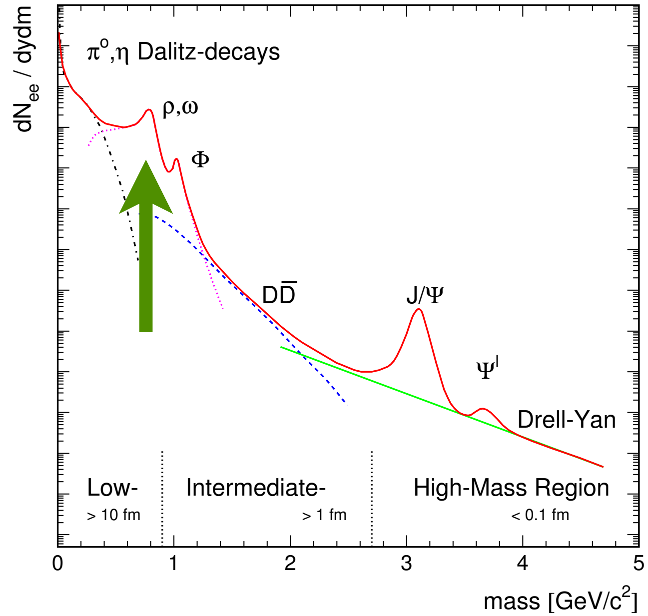


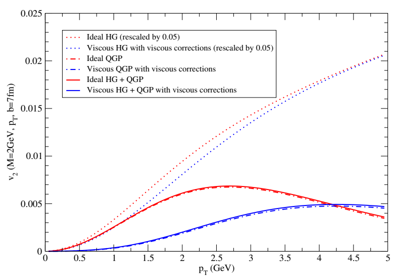
- Additional degree of freedom (M) provides flexibility
- By tuning M, open window on different aspects

G. Vujanovic, 2011-12

THERMAL DILEPTON V_2 WITH VISCOUS EFFECTS







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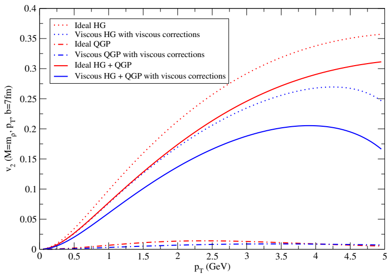

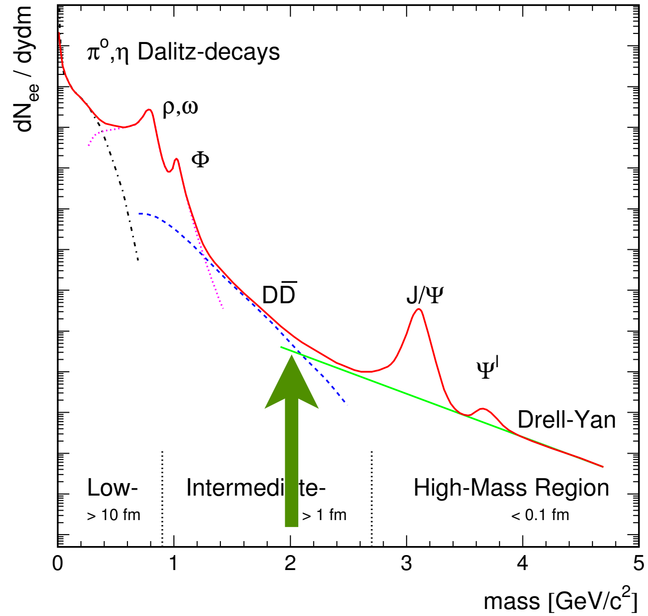

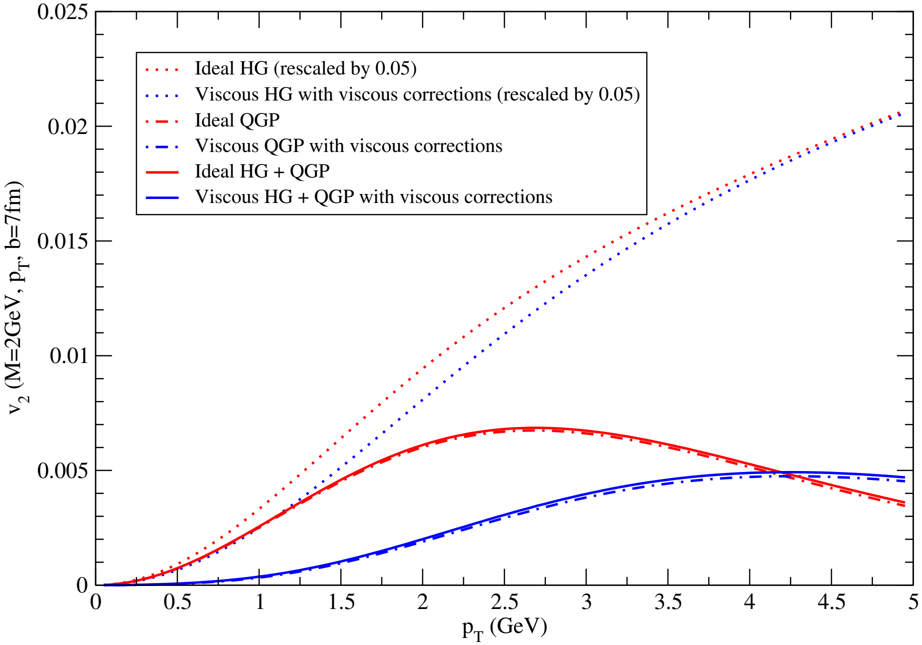

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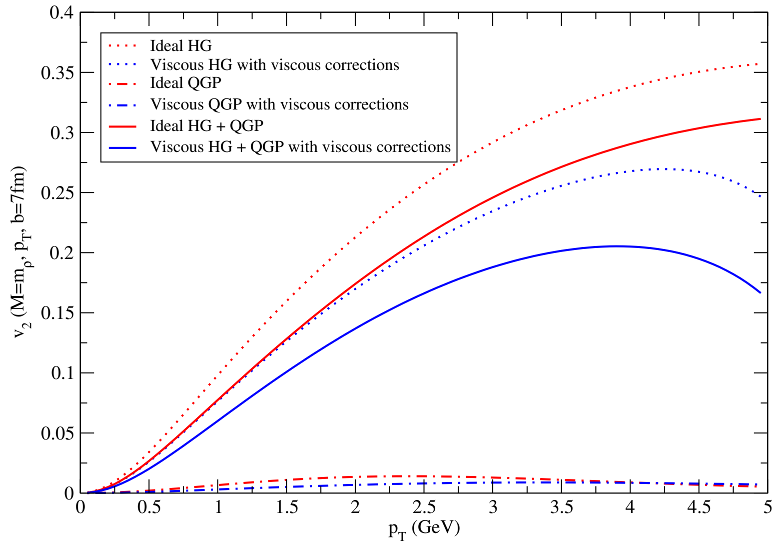

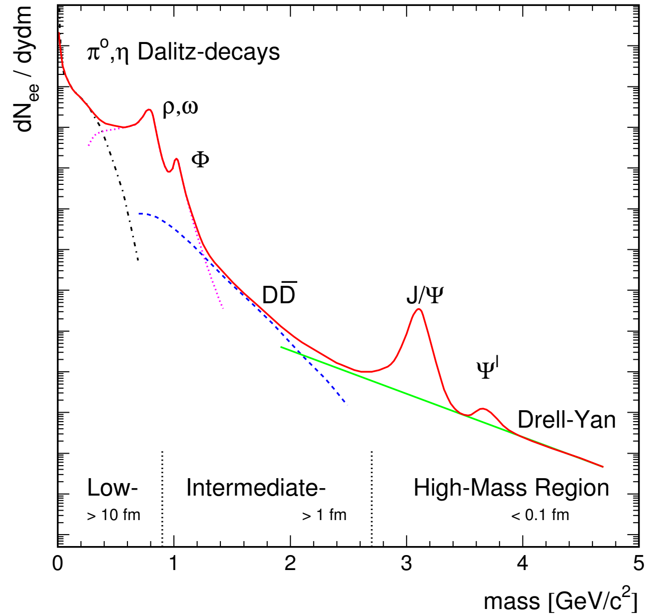

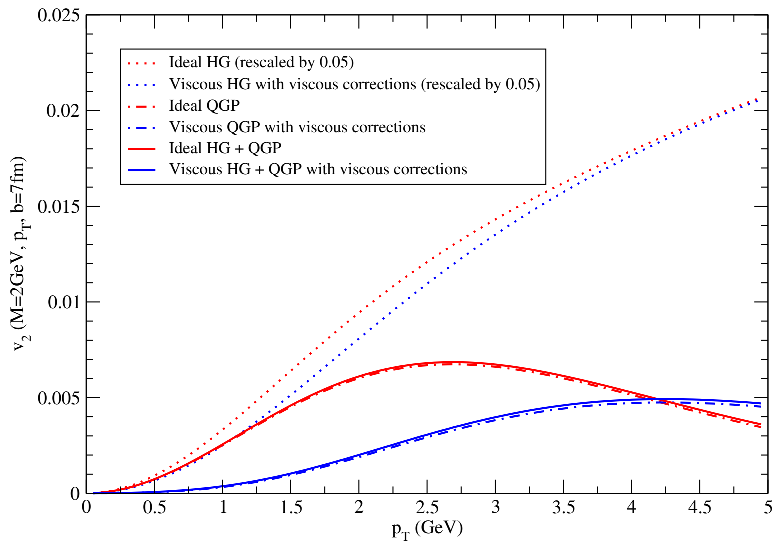

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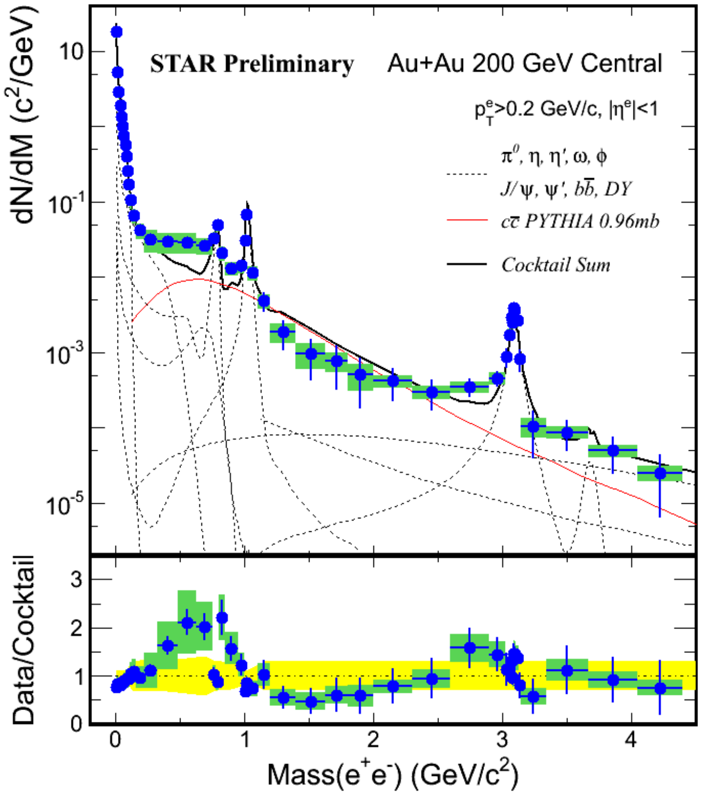
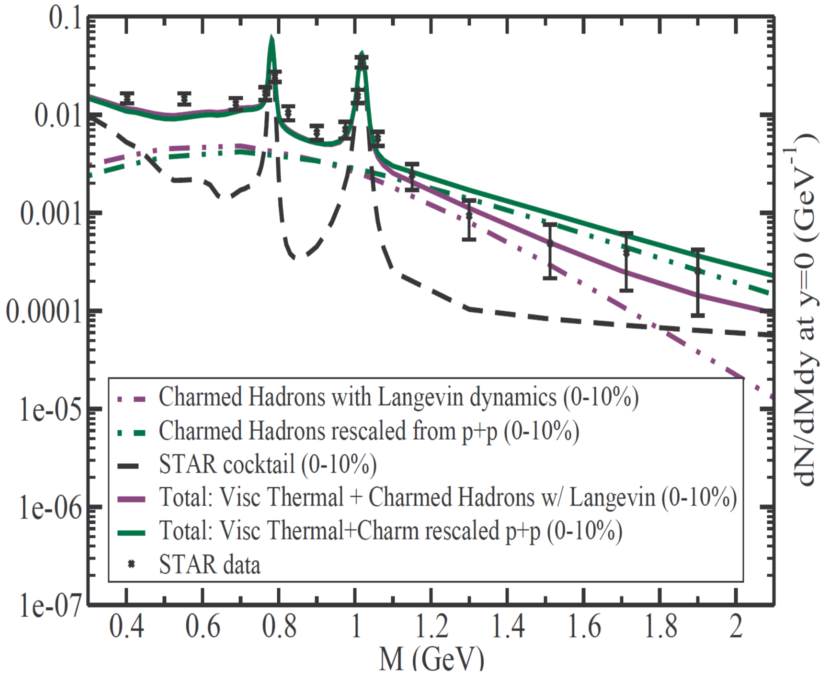
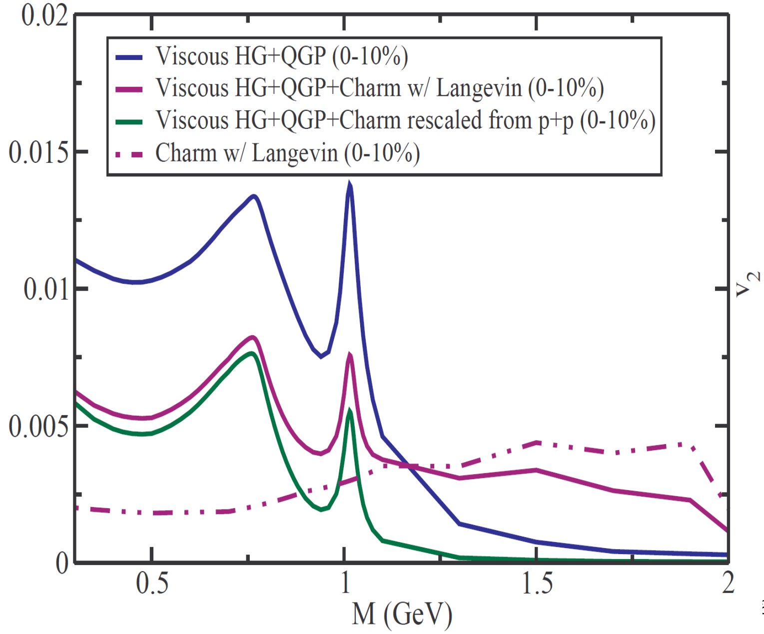
Dileptons, some recent results



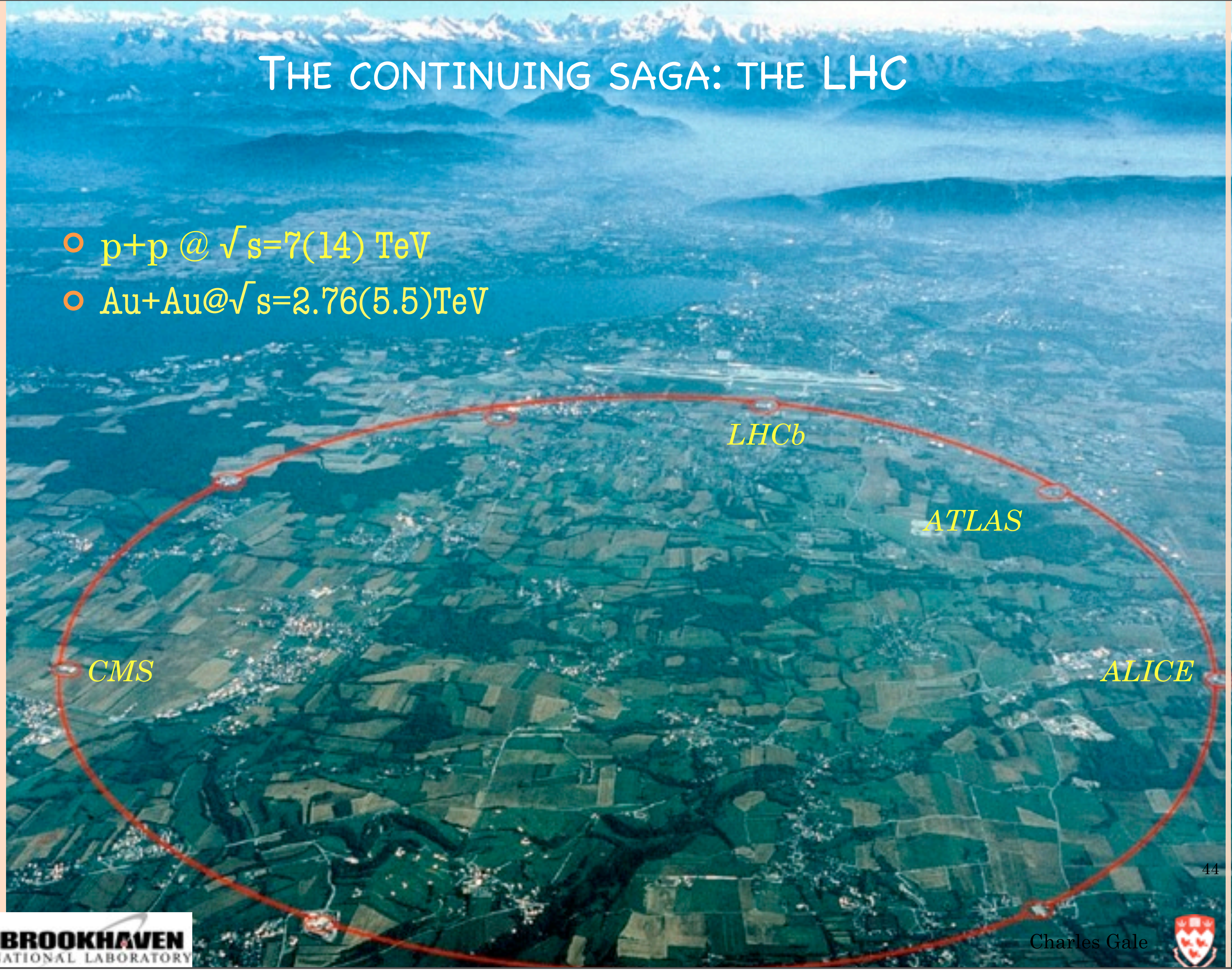




- High mass region and v_2, sensitive to heavy quark energy loss in the plasma
- Same ingredients used for interpretation of NA60 data
- STAR & PHENIX: differences

The continuing saga: the LHC

- p+p @ $\sqrt{s}$=7(14) TeV
- Au+Au@$\sqrt{s}$=2.76(5.5)TeV



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$\sqrt{s}$=2.76 TeV !!!

$\sqrt{s}$=2.76 TeV !!!

- . . .

$\sqrt{s}$=2.76 TeV !!!

- . . .

$\sqrt{s}$=2.76 TeV !!!

- . . .
- m≈2 mg, v≈2 km/h

$\sqrt{s}$=2.76 TeV !!!

- . . .

- m≈2 mg, v≈2 km/h

$\sqrt{s}$=2.76 **TeV !!!**

- . . .
- $m \approx 2$ mg, $v \approx 2$ km/h
- $E_k = 3 \times 10^{-7}$ J = 1.9 TeV

Charles Gale

$\sqrt{s}$=2.76 **TeV !!!**

- . . .
- $m \approx 2$ mg, $v \approx 2$ km/h
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$\sqrt{s}$=2.76 TeV !!!

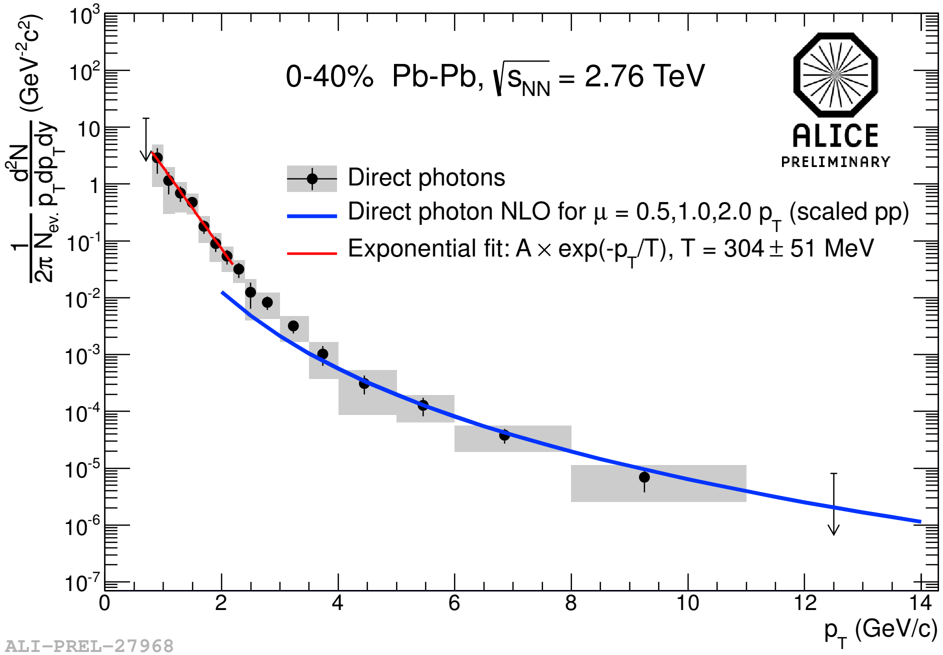
- . . .

- $m \approx 2$ mg, $v \approx 2$ km/h

- $E_k = 3 \times 10^{-7}$ J = 1.9 TeV

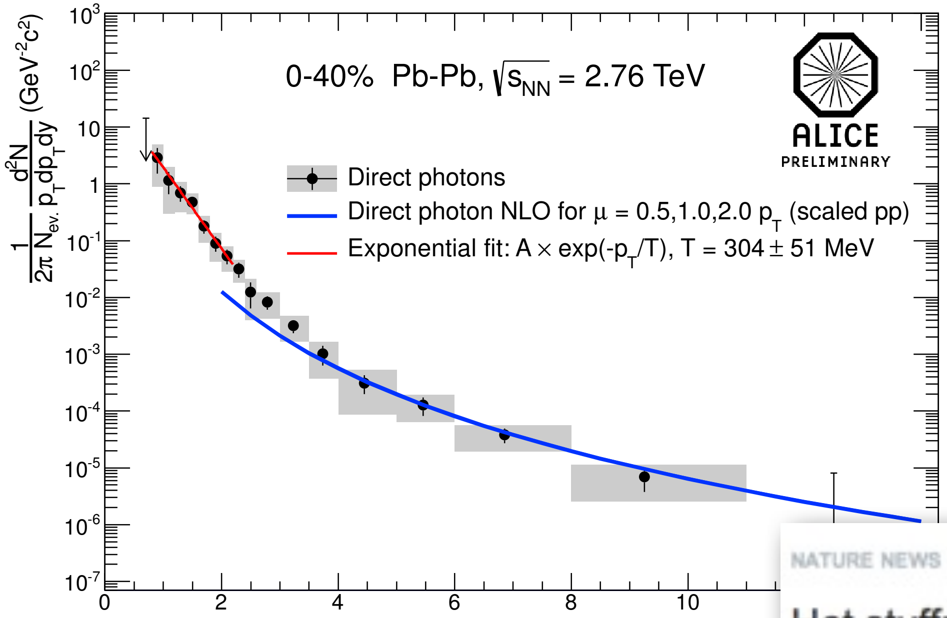
- An LHC collision = same as the kinetic energy of a flying moskito (in a volume ~ 10^{-13} smaller!)

The LHC as a thermometer



- Interpreting as a thermal source: T_{eff} = 300 MeV
- Recall that, at RHIC, T_{eff} = 220 MeV

The LHC as a thermometer



ALI-PREL-27968

- Interpreting as a thermal source: T_{eff} = 300 MeV
- Recall that, at RHIC, T_{eff} = 220 MeV

Now 38% hotter!

NATURE NEWS BLOG

Hot stuff: CERN physicists create record-breaking subatomic soup

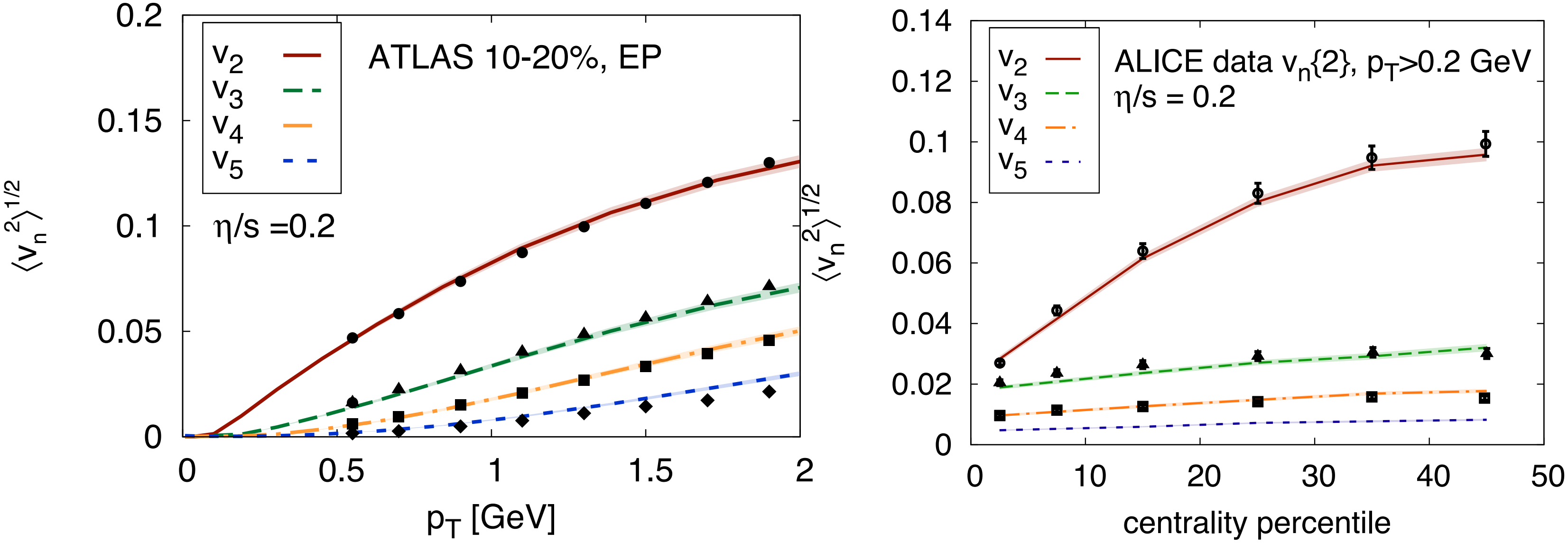
13 Aug 2012 | 23:58 GMT | Posted by Eric Hand | Category: Physics & Mathematics

Get Guinness. Physicists at CERN's Large Hadron Collider near Geneva, Switzerland, have achieved the hottest manmade temperatures ever, by colliding lead ions to momentarily create a quark–gluon plasma, a subatomic soup and unique state of matter that is thought to have existed just moments after the Big Bang.

CERN

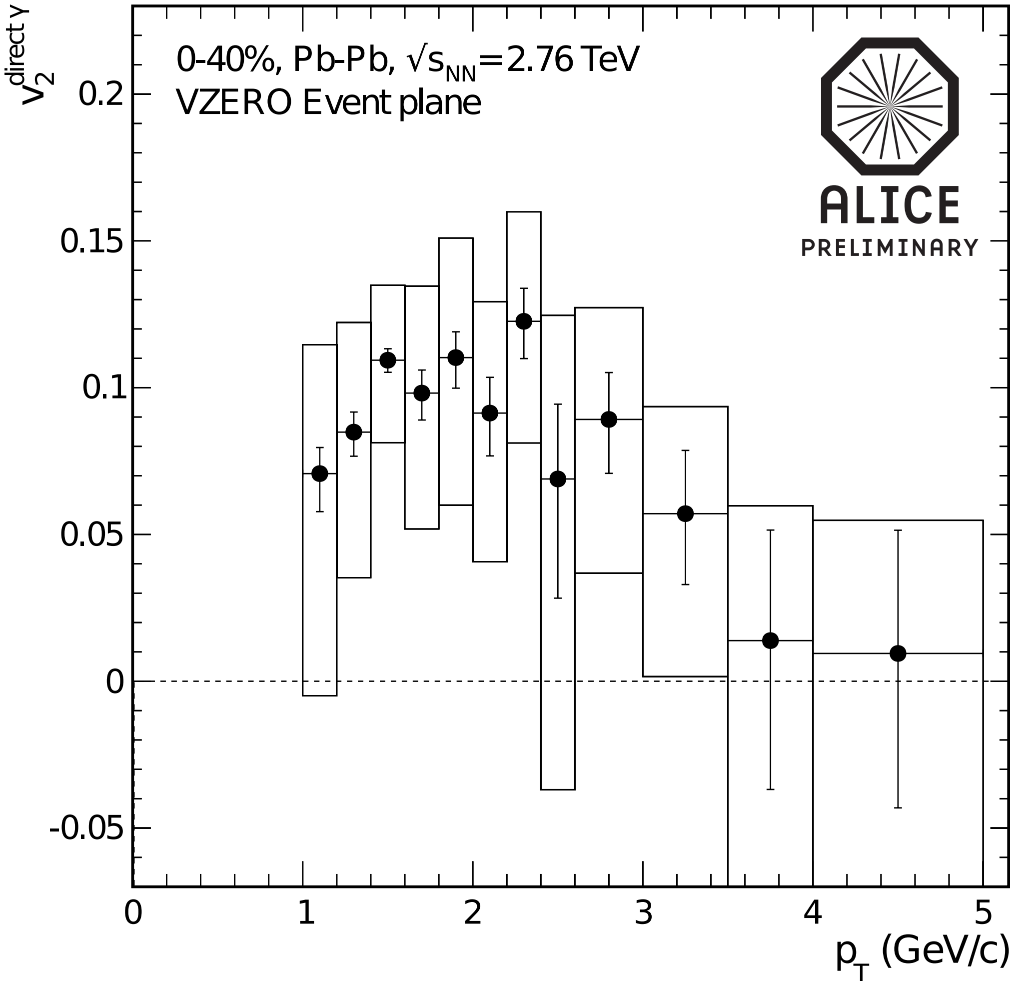
The results come from the ALICE heavy-ion experiment (at right) — a lesser-known sibling to ATLAS and the Compact Muon Solenoid, which produced the data that led to the announcement in July that the Higgs boson had been discovered. ALICE physicists, presenting on Monday at Quark Matter 2012 in Washington DC, say that they have achieved a quark–gluon plasma 38% hotter than a record 4-trillion-degree plasma achieved in 2010 by a similar experiment at Brookhaven National Laboratory in New York, which had been anointed the Guinness record holder.

The LHC as a viscometer



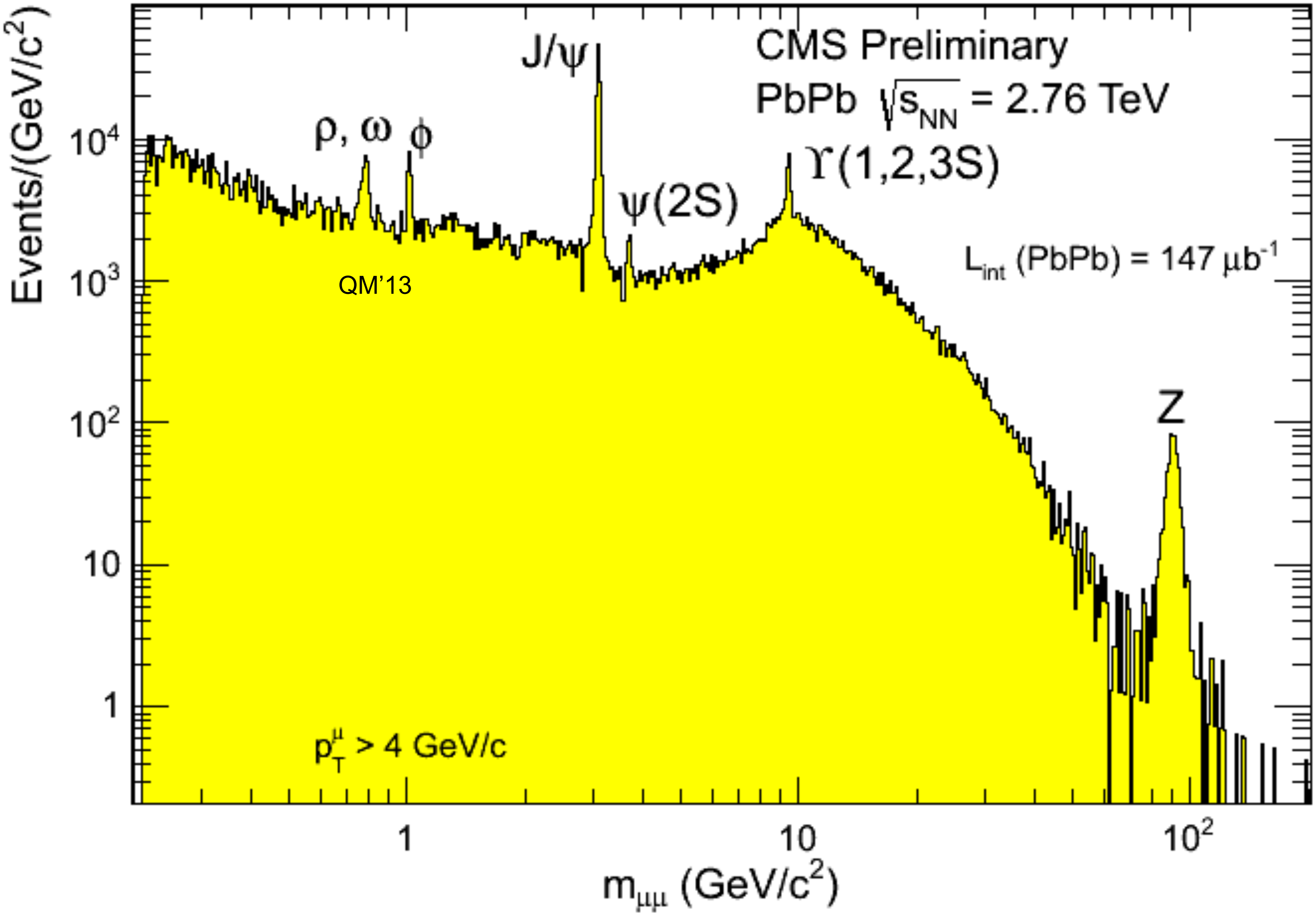
- This study establishes a sensitivity to the specific shear viscosity
- Data seems to be consistent
- More work needed to understand the evolution of viscosity between RHIC and the LHC

PHOTON V$_2$?



- Photon elliptic flow is as big as it is at RHIC
- Larger than hydro results

DILEPTONS?


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int} (PbPb) = 147 μb^{-1}
p_T^{μ} > 4 GeV/c
ρ, ω
φ
J/ψ
ψ(2S)
ϒ(1,2,3S)
Z
QM'13
Events/(GeV/c^2)
$m_{\mu\mu}$ (GeV/c^2)

CONCLUSION

- A **large** portion of the RHIC AA program not discussed here (jet E-loss, photon-tagged jets, chiral magnetic effect,...)
- The QGP has very low specific viscosity; connection with ultracold Fermi gases and string theory: A rapprochement between string theory and strong interaction phenomenology
- Moving closer to ab-initio modeling, which implies a quantitative knowledge of the initial state
  - Hadrons: Viscosity
  - Photons & Dileptons: Temperature
- This modeling incorporates our current knowledge of non-perturbative QCD ➡ "Standard Model"
- Many aspects not yet understood: not incremental
- Photon elliptic flow is new physics
- Dileptons: much more to come!
- Comparisons between RHIC and LHC essential